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Clinical Mechanics Group

of

Queen's University

Presents

Section D

Validation of the Load Carriage Simulator:

Research and Development
of an
Advanced Personal Load Carriage System (Phase 1)

submitted to

Defence and Civil Institute for Environmental Medicine

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Validation of the Load Carriage Simulator

Abstract

A comprehensive measurement system for load carriage evaluation was developed and described in Section B of this report. This measurement system consisted of human input with respect to comfort, features and fit, as well as a standardized measurement system using a computer-controlled Load Carriage (LC) Simulator. The LC Simulator had been programmed to a walking cadence of 3 km/hr using computer controlled pneumatic actuators. Three pack assessment strategies were used to examine the effect of pack dynamics with respect to a standardized mannikin: a) strap force sensors on the shoulder straps and waist belt; b) pressure sensors under the shoulder and waist straps and lumbar pad; and, c) differences in motion between the pack and the person.

The purpose of this portion of the study was to validate the measurement systems used in the LC Simulator under both static and dynamic conditions, and to conduct a sensitivity analysis of the biomechanical model used to evaluate shoulder and lumbar forces.

In order to accomplish the first objective, independent measurement strategies were formed for each of the LC Simulator output measures. The second objective of validating the biomechanical model was initiated by developing a standardized jig for shoulder strap testing where strap forces, pressures, shoulder geometry and pack conditions could be evaluated independently. Custom-built shoulder strap and waist belt force transducers were used in static and dynamic conditions to assess standardized weights. The calibration algorithms were gauge dependent and highly linear ($R^2 >$ .9995), with a small error (2.7 N) and were very stable over time in static testing. Under dynamic conditions the maximum standard deviation within tests was 0.9 N and across tests was 2.3 N with less that 4% decay over 1200 cycles.

The TECSCAN™ Pressure Sensor System under static conditions was more stable in average pressure and area of coverage than peak pressures, with the absolute value of peak pressures being more responsive to wrinkles in shirts or buckles. During dynamic conditions, over 1200 seconds of simulated walking trials, the SEM for average pressures was .5 kPa to 1.3 kPa depending on the location and pack characteristics. Peak values were less stable (SEM of 3.7 kPa to 12.6 kPa), dropped in magnitude over time, and were better suited to identifying pressure points.

The FASTRAK™ assessment of relative displacement between the pack and the person was validated with the OPTOTRACK™ system under both static and dynamic conditions. Results from the OPTOTRACK™ were transposed to correspond to a common coordinate system and a coincident measurement point. Regardless of test conditions, the pack/person relative positions had a .65 mm RMS error.

In the earlier biomechanical model reported in Section B, the upper shoulder strap (T2) was estimated from the lower shoulder strap (T1) tension, the shoulder wrap angle (θ) and approximations of the frictional forces (μ). The first step of the validation involved determining μ by two independent strategies. One calculation technique involved using the values for the upper and lower strap forces and the angle of wrap while the second incorporated the pressure generated under the strap with the two strap forces. There was no significant difference in the results from the two different methods ($R^2 > .92$). Hence, either method can be used to determine the upper shoulder strap forces (T2). Further research is ongoing to validate the shoulder reaction force, load lifter straps, and to incorporate the waist belt.

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Section D1

Summary of the Validation Studies

D1.1 Introduction

D1.2 Comprehensive Measurement System

D1.3 Specific Objectives of Section D

D1.4 Major Findings

D1.5 Recommendations

D1.1 Introduction

In October 1994, a research team at Queen's University was tasked by the Defence and Civil Institute of Environmental Medicine (DCIEM) to participate in the Canadian Land Forces Protective Clothing and Equipment (IPCE) Master Plan. This plan is part of the NATO Soldier Modernization Plan to develop an integrated "soldier system" to protect soldiers in modern technology warfare, and in peacekeeping roles. Because numerous military and civilian research and development agencies will be involved in the IPCE Project, it is necessary to provide the ability to respond quickly to proposed changes in items of soldier clothing and/or equipment. Hence, the second objective was to develop a comprehensive measurement system for evaluating the design and performance of current Personal Load Carriage Systems (PLCS). Specifically, the four objectives of this contract were to:

1. Document the current status of military (Canadian, British, and American) and civilian (internal and external framed) load carriage systems,
2. Develop a comprehensive measurement system for evaluating current designs and performance of personal load carriage systems (PLCS),

3. Determine the design and performance guidelines for a state-of-the-art advanced personal load carriage system (APLCS), and to
4. Validate the results from the standardized measurement system.

Objectives 1-3 have been reported in "Research and Development of an Advanced Personal Load Carriage System (Phase 1)" dated September 30, 1995 under Contract # W7711-4-7225/01-XSE. Other than providing an overview of the comprehensive measurement system, this report will be devoted to Objective #4 which is defined by the following objectives; namely to,

1. Validate the results of the Load Carriage Simulator, and to
2. Conduct a sensitivity analysis of the biomechanical model.

D1.2 Comprehensive Measurement System

The objectives of the comprehensive measurement system were to develop an accurate and reliable assessment strategy for load carriage systems that was rapid and cost effective. To accomplish this objective, human input on comfort and fit were quantified and compared to standardized input from a Load Carriage (LC) Simulator. To acquire human input, two circuits were developed: 1) an agility circuit was designed to be representative of critical survival skills common to military tasks, and 2) an endurance circuit as represented by an extended march. The standardized performance measurements were established using a computer-driven Load Carriage (LC) Simulator and a torsional stiffness testing system. Human responses were compared to LC Simulator measures in order to rank five packs that were selected to represent military and civilian (PLCS).

The LC Simulator was constructed by the Clinical Mechanics Group of Queen's University and Kingston General Hospital. A scaled model of the human torso was affixed to a moving table which cycled through the displacement of a walking cadence of three kilometres per hour using computer-controlled pneumatic actuators. The mannikin was instrumented to determine the relative motion between the pack and the torso using FASTRAK™ electromagnetic sensors. Custom strain gauges were design to measure strap forces, and the TEKSCAN™ pressure sensor system was used to assess contact pressures between the torso and the pack suspension elements. Based on strap

forces, body incline, weight in the pack and anthropometric measures of the pack and mannikin, a biomechanical model was developed to predict the shoulder and lumbar joint reaction forces. The validation of these measurement systems and the biomechanical model that are central to this report.

D1.3 Specific Objectives of Section D

There are four aspects to the validation of the LC Simulator:

1. An investigation of the accuracy and precision of the strap gauges, the pressure sensor system and the pack/person motion system in comparison to gold standards under both static and dynamic conditions,
2. An assessment of the validity and repeatability of these LC Simulator values through repeated measures of the Canadian system,
3. An examination of the repeatability of rank order results by comparing the rank order of the Canadian and Dru PLCS, and
4. A validation of the biomechanical model of the pack, beginning with the validation of the shoulder forces and pressures.

These objectives will be presented based on the measurement systems used and reported under the two major headings of a) Validation of the LC Simulator and b) Load Carriage Biomechanical Model. In addition, LC Simulator protocols are documented in Appendix 9 included in this report.

D1.4 Major Findings

The measurement devices used to assess the forces in the straps, pressure on the skin, and relative pack/person motion were customized force transducers, a pressure sensing system and a 3D motion sensing system. A summary of the significant findings from the validation and reproducibility studies is presented in Table D1.1. These results are based on test-retest or repeated measures of the Canadian Forces 1982 pattern rucksack or the Gregory 'Dru' backpack.

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Table D1.1 - Summary of significant findings from validation and reproducibility study

Test Parameter and Method of Validation	Results - Accuracy, Precision and Reproducibility
Strap Force Transducers	
Static - Strap transducer response versus calibrated weight **Dynamic** - Independent level walking tests, CF 1982 pattern load carriage	**Test range** : 0 - 100 N, **SD**: Waist = 1.5 N, Shoulder = 2.6 N, **SD** (independent tests): Waist = 0.9 N, Shoulder = 0.3 N **SD** (all tests): Waist = 2.4 N, Shoulder = 2.3 N **Decay** over 1200 cycles: <4%
Pressure Distribution	
Static - Independent tests, CF 1982 pattern load carriage and Gregory Dru backpack	Good test to test correlation of average pressures Good agreement of average pressure with previous report Confirmation of pack rank orders from previous tests
Dynamic - Test/retest of CF 1982 pattern load carriage and Gregory Dru backpack	Good test to test correlation of average pressures **SD** (average pressures, 1200 cycles): 2.6 kPa **Samples** needed for **SEM<2.0 kPa**: n=2
Dynamic - Independent level walking tests, CF 1982 pattern load carriage	Good repeatability on the locations of peak pressures Marginal repeatability on the magnitude of peak pressures **SD** (peak pressures, 1200 cycles): 12.6 kPa
Relative Displacement of Pack	
Static - Fastrak™ data versus Optotrak™ displacement data **Dynamic** - Independent level walking tests, Fastrak™ data versus Optotrak™ data	**RMS** error (relative pack/head displacement): 0.65 mm **Relative displacement** (peak to peak): Fastrak = 5.3 mm, **RMS** error (relative pack/head displacement): 0.65 mm

* Statistical analyses were either test-retest or repeated measures designs

In the initial study a biomechanical model, which took into account: body lean, load magnitude, location of load centre of mass, and the strap angles was developed using the results from the shoulder strap force transducers. Using this simplified model, and assumptions about: frictional forces, point force locations, and the shoulder/waist reaction force locations, the packs were assessed for the magnitude of shoulder and lumbar pad reaction forces. These values were used to rank order the packs and compare forces and pressure values to suggested tolerance limits from the scientific literature. In the earlier biomechanical model, the upper shoulder strap (T2), was estimated from the lower shoulder strap (T1) tension, the shoulder wrap angle (θ), and approximations of the frictional forces (μ). To refine and validate the original model, a theoretical framework for the shoulder reaction forces was developed. The validity of the model was assessed by comparing the effect of using two different model inputs: strap forces and strap pressures. There was no significant difference between the two methods used to calculate μ across varying loads and wrap angles ($R^2 >$ .92). Therefore, either method can be used to determine the upper shoulder strap forces (T2). These results confirm the appropriateness of the shoulder model. Further research is ongoing to validate the shoulder reaction force, load lifter straps, and to incorporate the waist belt.

D1.5 Recommendations

Based on the validation of the measurement systems used in the L C Simulator and on the initial studies to examine the shoulder strap forces, pressures and joint reaction forces, the following recommendations are made:

1. The measurement systems used in the Load Carriage Simulator are sufficiently accurate and precise within the documented errors identified in Table D1.1 of this report. Therefore, the standardized assessment system can be a valuable asset in evaluating and ranking various pack-based systems as well as future IPCE designs.
2. The biomechanical model was used to determine the shoulder and lumbar forces based on the pack, its weight, shoulder strap orientation and extent of body lean. For the shoulder, the initial model is accurate for estimating the upper shoulder strap. However, it is not sufficiently sophisticated to estimate the shoulder reaction forces. In addition the waist belt has not been incorporated into the model. Therefore, based on the success to date and a clearly delineated sequence of validation steps, additional research should be conducted on the biomechanical model of the load carriage system.

Section D2

Validation of the L C Simulator

D2.1 Strap Force Transducers - Static Test

D2.2 Strap Force Transducers - Dynamic Test

D2.3 Pressure Sensing System - Static Test

D2.4 Pressure Sensing System - Dynamic Test

D2.5 Relative Displacement of Pack - Static Test

D2.6 Relative Displacement of Pack - Dynamic Test

A validation procedure is one in which an independant measurement system is used to determine the accuracy and precision of a piece of equipment or the validity and reliability of a testing protocol. For example, the suspension of a series of weights on a strain gauge transducer can be used to assess the accuracy and precision of the electronic measurement system through a range of forces. Likewise, a previously validated measurement system (such as the OPTOTRACK™) can be used as an independant comparison with data acquired from the Fastrak™ system. When this equipment is used in biomechanical modelling, it is also important to use independant strategies to derive comparisons (i.e. derive the shoulder joint reaction forces either from strap forces or from strap pressures). The purpose of Section D2 was to validate the measurement systems used in the LC Simulator.

D2.1 Strap Force Transducers - Static Test :

Introduction

In the current LC simulator system, strain gauges are used to measure the tension in the lower shoulder strap attachment and the waist belt of each pack. This measurement was used as a method for standardizing the strap tensions of the pack on the model torso from test to test.

To ensure accurate results from strain gauges it is important to follow a repeatable calibration technique.

Methodology

The two strain gauge transducer systems were removed from the shoulder and waist straps. With each gauge in a no load condition, the output voltage from the bridge was balanced. This value was used as the system offset voltage in the data acquisition program.

The strain gauge transducer was placed into a vertical position with top end support and a cable for supporting mass was extended from the inferior end of the transducer. A primary strain gauge voltage output recording at load equal to 0 N was made. Further readings in this load condition were made after 1 minute and 3 minutes. A load of 44.5 N was affixed to the support cable. Output voltage readings were taken at time = 0, 1, and 3 minutes of loading. This test was repeated with loads of 89.0 N, 133.2 N, and 177.5 N. Results were recorded for all three time intervals.

This entire test protocol was repeated four times for each strain gauge transducer system.

Results

Table D2 - 1 shows the data, as well as the standard deviation, for the waist belt transducer. The correlation coefficient values were used to compare the linearity of the calculated and experimental values. Calculated output values were based on strain gauge theory, such that :

$$\sigma\ [\text{kPa}] = \text{Force}\ [\text{N}] / \text{Cross Sectional Area}\ [\text{m}^2] \quad \text{where } \sigma = \text{stress}$$

$$\epsilon\ [\text{m/m}] = \sigma\ [\text{kPa}] / E\ [\text{kPa}] \quad \text{where } \epsilon = \text{strain and } E = \text{Young's Modulus}$$

$$V_{OUT}\ [\text{V}] = V_{IN}\ [\text{V}] * \text{Gauge Factor} * \epsilon\ [\text{m/m}]$$

for a temperature compensated Wheatstone bridge with two active gauges

Similar calculations and results for the shoulder strap transducer are found in Table D2 - 2.

Waist belt transducer values for data collected at times equal to 0, 1 and 3 minutes of strain duration can be found, with standard deviations, in Table D2 - 3.

Discussion :

The maximum sample standard deviation in the waist transducer was 0.006 V (1.5 N) and is 0.01 V (2.6 N) in the shoulder strap transducer. These small values indicate that the repeatability of the output voltage from the strain gauge, under the same load, is quite high. Similarly, the high correlation coefficients (r squared value > 0.9995 in all cases) indicates that the output from the gauges is extremely linear. Table D2 - 3 shows that there was no change in output voltage from a transducer over an extended loading period, indicating that self heating and drift are not seen in this setup. For this reason, data were not included in this report for the time varied data in the shoulder strain gauge transducer.

Conclusions and Recommendations :

The following conclusions were made :

1. The current strain gauge transducers were very stable over an extended test period.
2. The maximum standard errors of the strain gauge data were quite small, 1.5 N (0.006 V) for the waist and 2.6 N (0.022 V) for the waist.
3. The high correlation coefficients ($R^2 > 0.9995$) indicated that the data is highly linear. This allowed for the development of accurate calibration equations for converting output voltage to a load value.

   For this experiment, the equations were :

   $$\text{Load (N)} = V_{OUT}\text{ (V)} / 0.004245 \quad \text{[WAIST]}$$

   $$\text{Load (N)} = V_{OUT}\text{ (V)} / 0.0046173 - 0.002104 \quad \text{[SHOULDER]}$$

The following recommendations were made :

1. The lead wires from the strain gauge bridges should be lengthened to allow for more manouverability, especially in the field.
2. Connections of the gauges to the load carriage straps should be inspected and improved where possible.

Table D2 - 1 - Static Test - Waist Strain Gauge Transducer

Applied Load (N)	Calculated Output Voltage (V)	Trial 1 Output Voltage (V)	Trial 2 Output Voltage (V)	Trial 3 Output Voltage (V)	Trial 4 Output Voltage (V)	Variance (V^2)	STDS (V)
0.00	0.000	0.000	-0.010	0.000	-0.010	0.00003	0.005774
44.49	0.212	0.190	0.185	0.195	0.180	0.000153	0.006455
88.98	0.424	0.385	0.375	0.390	0.380	0.000383	0.006455
133.24	0.636	0.565	0.560	0.570	0.560	0.001048	0.004787
177.50	0.847	0.750	0.750	0.750	0.750	0.001869	0
R Squared		0.9998	0.9999	0.9996	0.9998		

Table D2 - 2 - Static Test - Shoulder Strain Gauge Transducer

Applied Load (N)	Calculated Output Voltage (V)	Trial 1 Output Voltage (V)	Trial 2 Output Voltage (V)	Trial 3 Output Voltage (V)	Trial 4 Output Voltage (V)	Variance (V^2)	STDS (V)
0.00	0.000	0.000	0.003	0.003	0.004	3.5E-06	0.001732
44.49	0.212	0.209	0.209	0.205	0.205	9.4E-06	0.002309
88.98	0.424	0.424	0.424	0.415	0.410	0.000044	0.006946
133.24	0.636	0.630	0.630	0.610	0.610	0.000148	0.011547
R Squared		0.9999	0.9999	0.9998	0.9999		

Table D2 - 3 - Static Test - Time Variation in Waist Strain Gauge Transducer Output

Applied Load (N)	Trial 1 Time = 0 min Output Voltage (V)	Trial 1 Time = 1 min Output Voltage (V)	Trial 1 Time = 3 min Output Voltage (V)	Variation (V^2)
0.00	-0.005	-0.005	-0.005	0.0
44.49	0.190	0.190	0.190	0.0
88.98	0.385	0.385	0.385	0.0
133.24	0.565	0.565	0.565	0.0
177.50	0.750	0.750	0.750	0.0

D2.2 Strap Force Transducers - Dynamic Test

Introduction

Measuring the force transmitted through the shoulder and waist belt straps is important as a method of ensuring that the straps of the load carriage system are secured to a repeatable tension range from test to test. This quantity may have a direct effect on the values recorded for relative pack displacement and surface pressures generated by load carriage/wearer contact during dynamic testing by varying the possible motion of the pack. For this reason it must be repeatable from test to test.

Methodology

A standardized test trial (see Appendix 9) was conducted. Strap force data were collected at test times of 10, 300, 600, 900, and 1200 seconds from strain gauge transducers in full tension, located in the left shoulder strap and the waist belt of the Canadian 1982 Pattern Rucksack. Data were converted from voltage output to force by means of a linear calibration curve (see Section D2.1), individually generated for each transducer. In total, four test trials were conducted.

Results

Table D2 - 4 shows the results of all four trials, with averages and sample standard deviations across trials calculated. A visual representation of these results can also be found in Figures D2 - 1(a) and (b). Figure D2 - 2 shows the results for a standard testing cycle with maximum, minimum, and mean strap forces calculated for the waist belt and shoulder straps.

Discussion

Transducer Validation - Independent Trials :

The strap force magnitudes for both the shoulder strap and the waist belt show only small changes over the duration of any one trial, as seen in Table D2 - 4 and in Figures D2 - 1(a) and (b). For trials 2 - 4, the maximum standard deviation for the shoulder strap force mean is 0.3 N and in the waist belt the maximum variance of the mean force is 0.9 N. This result shows that for any one test, the variability of the strap forces over the trial duration is quite small. Trial 1 was not included in these calculations because of a protocol error that occurred during testing. The discontinuity of the mean strap forces, as shown in Figures D2 - 1(a) and (b) for Trial 1, were caused by uncontrolled

simulator settling during a test pause at a cycle time of 500 seconds. This settling allowed for irregular pack motion and therefore uncharacteristic strap force values.

Transducer Validation - Multiple Trials :

The repeatability between the trials is also shown in Figures D2 - 1 (a) and (b). Standard deviations across trials are again quite small, with a value of 2.3 N for the mean shoulder strap force and 2.6 N for the waist belt.

Conclusions and Recommendations

As shown in Section D2.1, the strain gauge transducers are very accurate, with repeatable results, under static conditions. Therefore, it was possible to draw the following further conclusions from dynamic testing :

1. Strap force data were most useful as a standardization method to ensure that load carriage systems were tested under similar conditions.
2. The precision of the current strap force transducer system was greater than 2.7 N in all cases and the decay over 1200 cycles was less than 4.0 %.

These results led to the development of the following recommendations :

1. The consistency of test results during any one trial indicate that the loosening of straps in buckles is not as large a problem as was hypothesized prior to testing. For this reason, collection of strap force data in the future is not required at five minute intervals during a test. Data collections performed after 10 cycles of simulator motion and after 1200 cycles of motion (end of test) would provide enough information to evaluate the strap tension and also allow for another set of data (displacement values or pressure recordings) to be recorded at the same time. The small variance between trials illustrates that numerous trials need not be performed.

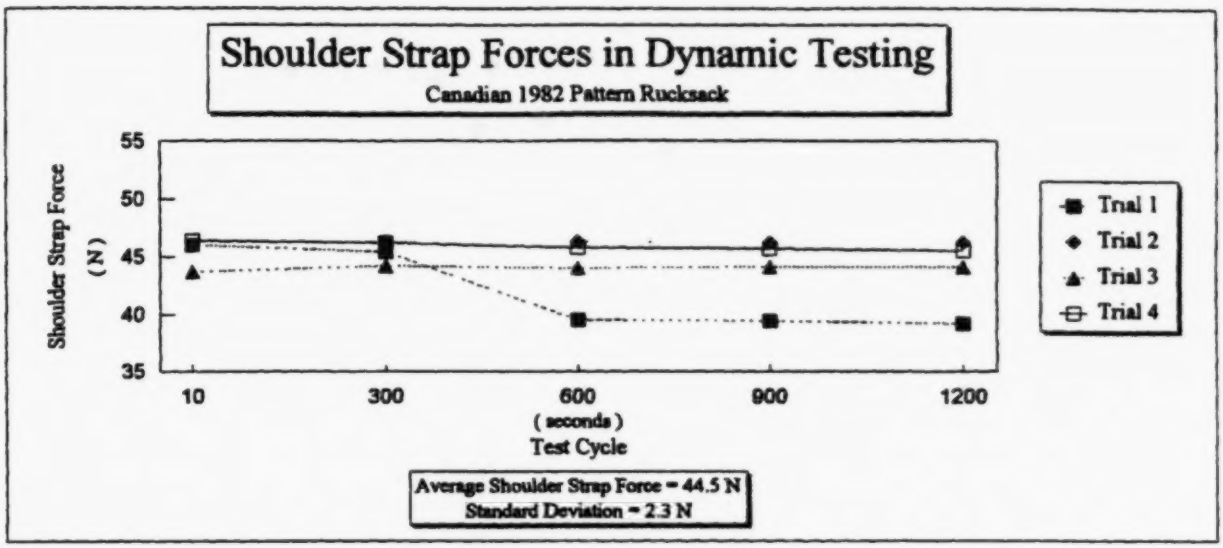
Table D2 - 4 - Strap Forces in Dynamic Testing of Canadian 1982 Pattern Rucksack

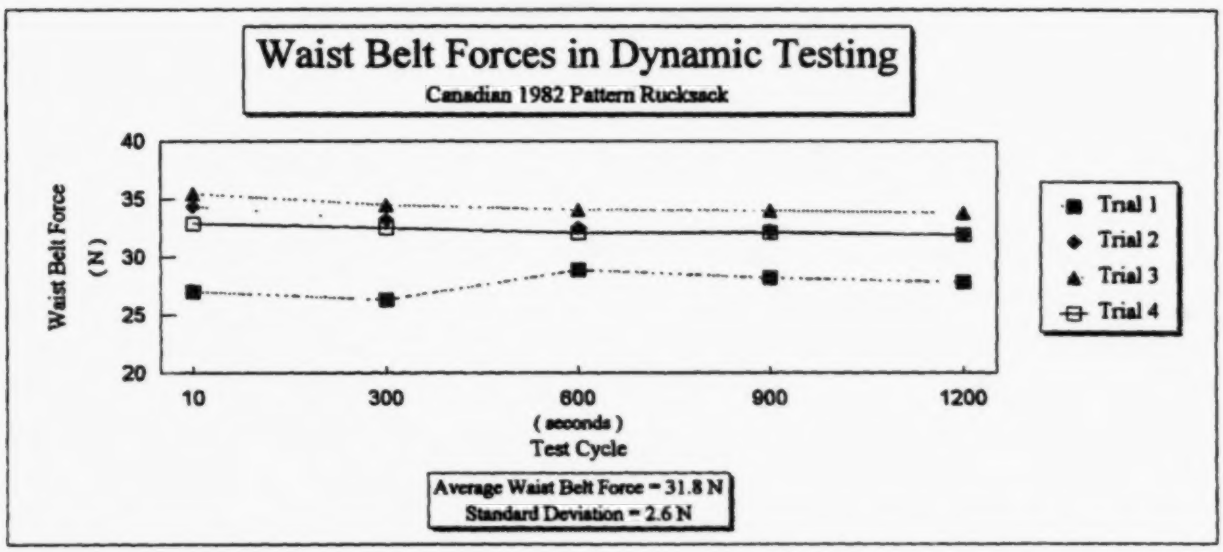
Strap Forces in Dynamic Testing Canadian 1982 Pattern Rucksack

Trial	Cycle	Shoulder Strap			Waist Belt		
		Maximum (N)	Mean (N)	Minimum (N)	Maximum (N)	Mean (N)	Minimum (N)
1	10	55.1	46.0	32.2	40.2	27.0	15.4
	300	57.6	45.4	28.8	40.8	26.3	14.8
	600	43.2	39.5	34.1	41.5	28.9	15.6
	900	42.9	39.4	34.4	40.2	28.2	15.7
	1200	43.8	39.2	34.1	39.8	27.8	15.1
Average (N)		48.5	41.9	32.7	40.5	27.6	15.3
STD (N)		6.4	3.1	2.1	0.6	0.9	0.3
2	10	49.4	46.0	39.2	44.5	34.4	23.9
	300	50.9	46.3	40.3	43.9	33.2	22.3
	600	49.9	46.3	41.1	42.4	32.5	22.7
	900	50.9	46.2	40.0	43.1	32.2	21.2
	1200	50.5	46.2	41.0	41.6	31.9	21.8
Average (N)		50.3	46.2	40.3	43.1	32.8	22.4
STD (N)		0.6	0.1	0.7	1.0	0.9	0.9
3	10	47.7	43.7	38.1	41.7	35.5	26.1
	300	49.1	44.2	38.8	41.4	34.5	26.0
	600	64.8	44.0	32.5	49.5	34.1	24.6
	900	49.3	44.1	37.4	41.6	34.0	26.4
	1200	49.7	44.1	39.2	41.4	33.8	25.3
Average (N)		52.1	44.0	37.2	43.1	34.4	25.7
STD (N)		6.4	0.2	2.4	3.2	0.6	0.6
4	10	54.3	46.4	37.2	40.1	32.9	23.8
	300	54.5	46.2	36.9	41.0	32.5	21.7
	600	53.9	45.8	35.7	39.6	32.1	21.7
	900	54.3	45.7	35.5	39.5	32.1	22.4
	1200	53.6	45.5	35.3	39.5	31.9	21.7
Average (N)		54.1	45.9	36.1	39.9	32.3	22.3
STD (N)		0.3	0.3	0.8	0.6	0.4	0.8
Average (N)		51.3	44.5	36.6	41.7	31.8	21.4
STD (N)		5.0	2.3	3.2	2.3	2.6	3.8

D13

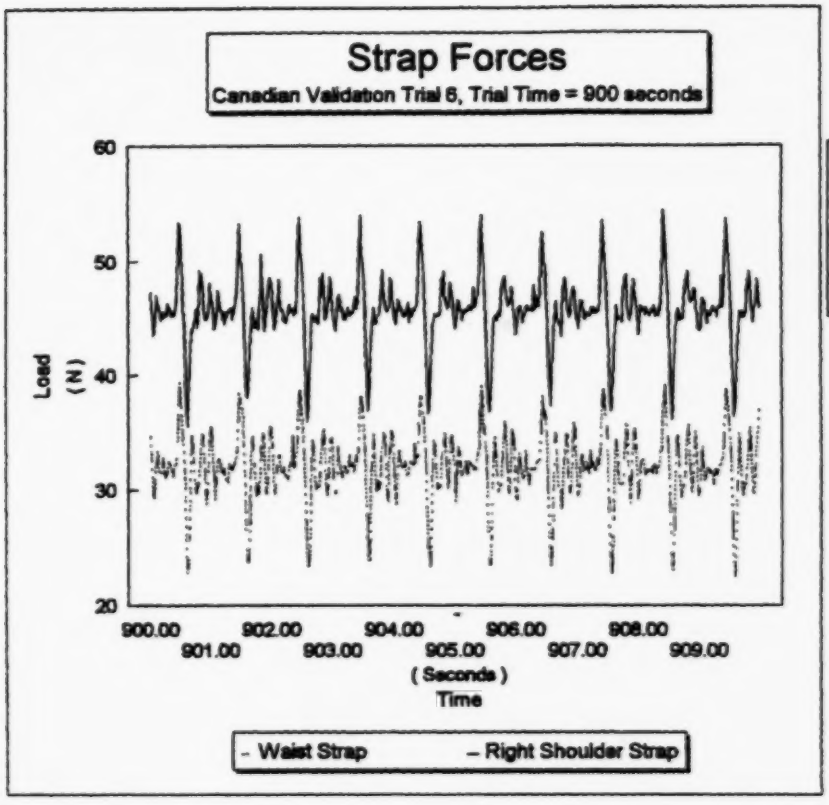
(a)





(b)

Figure D2 - 1 - Dynamic testing of strain gauge transducers.
(a) Shoulder Strap Transducer (b) Waist Belt Transducer



..	shoulder (N)	waist (N)
Max	54.331	39.465
Min	35.526	22.464
Mean	45.731	32.060
STDS	2.883	2.924

Figure D2 - 2 - Strap force transducer output for Canadian 1982 pattern rucksack, time = 900 cycles

D2.3 Pressure Sensing System - Static Test

Introduction

Contact pressures experienced by the wearer during load carriage are an important criterion for evaluating packs. The ability to consistently reproduce the pressure data in a static situation, as well as in a dynamic test, is valuable in confirming any pack quality rankings as well as validating the accuracy of the pressure sensing system.

Methodology

Testing followed the protocol of a typical pressure data collection experiment (see Appendix 9). Pressure sensors were affixed to the simulator torso in premarked contact areas, and these sensors were checked for a zero pressure value in a no load condition. Load carriage systems were packed with a payload of 245.3 N (25.0 kg). The load carriage system was then loaded onto the model and the torso was leaned forward until the reaction moments at the torso base balanced. Strain gauge transducers were used to ensure that strap tensions were set to values that were standard across all trials for that load carriage system. Pressure recordings at contact sites on the right shoulder, right side of waist, and centre of the lower lumbar were then taken. This process was repeated twice for the Canadian 1982 Pattern rucksack and three times with the Gregory Dru backpack.

Results

Figures D2 - 3 (a), (b), and (c) show the comparison of shoulder, waist, and lumbar static pressure results from both the Gregory Dru Backpack and the Canadian 1982 Pattern Rucksack. These data are also found in Table D2 - 5. Figures D2 - 4 (a) and (b) show comparative plots of the shoulder surface pressure generated by the Canadian 1982 Pattern Rucksack during two static trials while Figures D2 - 5 (a), (b), and (c) illustrate the shoulder surface pressure diagrams for the Dru pack. Table D2 - 6 compares the results of static and dynamic surface pressure testing with the Gregory Dru backpack.

Discussion

Trends are visible in the data in Figures D2 - 3 (a), (b), and (c) that indicate consistent results are provided by the pressure sensors during a static test. In the shoulder test figure (Figure D2 - 3 (a)), the contact pressures generated by the Canadian rucksack are consistently larger in both the average and local peak cases than the Dru pack. This result is visible again in the lumbar pressures (Figure D2 - 3 (c)) , but is reversed in the case of the waist pressure (Figure D2 - 3 (b)). All pressures associated with one anatomical location (ex. shoulder, waist, lumbar) and one load carriage system are close in value, as seen in Table D2 - 5 The larger variations in the peak values are understandable when considering the slight irregularities that can cause a severe pressure peak, ex. shirt seam, shirt wrinkle, sensor wrinkle, etc. Shirt seam artifacts also occur in dynamic testing (see Section D2.4) but cause less of a problem because they typically do not exist for an entire test.

This result of developing temporary pressure peak areas is visible in Figures D2 - 4 (a) and (b). The first figure shows a peak which is out of scale (51.7 kPa versus 39.6 kPa) with the second trial and with dynamic trials performed for this report (see Section D2.4). This peak zone is also located in an area that was a pressure high point, but not the most severe, in all other Canadian trials, static or dynamic (see Section D2.4). These two results indicate a transient pressure high point.

Comparison of the shapes, area, and high pressure zones in Figures D2 - 4 (a) and (b) for the Canadian pack and Figures D2 - 5 (a), (b), and (c) for the Dru confirm the repeatability of pressure results.

Conclusions and Recommendations

The results of static testing show that the current pressure sensing system is a valid means of quantifying contact pressure generating characteristics of various load carriage designs. However, comparison with the results of dynamic testing reported in Section B of the main report indicates that static testing does not adequately predict dynamic performance. Table D2 - 6 compares dynamic and static Dru results, showing that in the dynamic case shoulder surface pressures increase and waist pressures decrease. This result , caused by the pack shifting during dynamic activity, would make ranking packs based on static results inaccurate, demonstrating the need for dynamic testing. Dynamic values in the shoulder area were seen to approximately double the static readings, while lumbar pressures seemed to stay basically the same. Waist pressures were seen to drop significantly

between static and dynamic testing. These observations were another indication of the need for dynamic testing to properly evaluate load carriage designs.

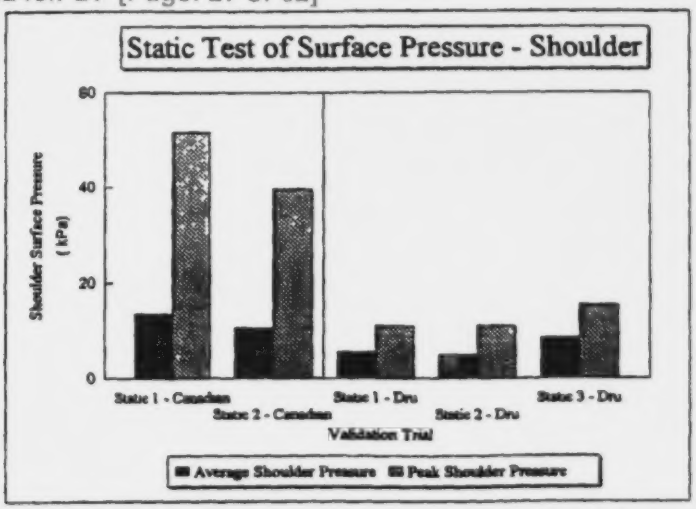
Currently, the torso model is covered with a standard issue Canadian military combat shirt. While this is a typical military clothing situation, it can lead to the development of transient pressure peaks at seams and wrinkles (A smooth, tight shirt of a stretchable material (ex. Lycra ™) would prevent much of this effect). These artifacts caused by clothing would not be representative of true human tests, since a load carriage wearer would shift their clothing where possible to reduce peak pressures. In LC simulator testing, it would be valuable to locate all peak pressures and their cause before initiating a test sequence.

Table D2 - 5 - Static test of surface pressure measurements

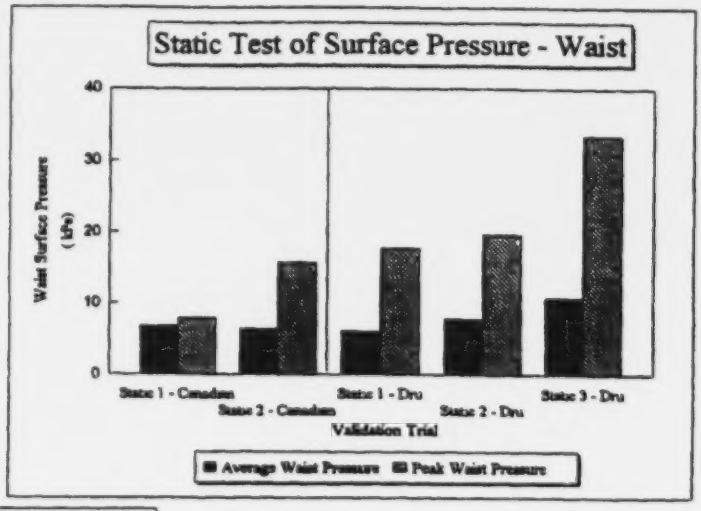
		Canadian		Dru		
		Trial 1 (kPa)	Trial 2 (kPa)	Trial 1 (kPa)	Trial 2 (kPa)	Trial 3 (kPa)
Shoulder	Average	13.6	10.5	5.5	5.0	8.5
	Peak	51.7	39.6	11.0	11.0	15.4
Waist	Average	6.8	6.3	6.0	7.8	10.8
	Peak	7.9	15.7	17.7	19.7	33.4
Lumbar	Average	10.7	11.0	8.0	7.8	10.3
	Peak	19.6	25.4	14.5	16.3	20.9

Table D2 - 6 - Comparison of static and dynamic pressure test for Gregory Dru backpack

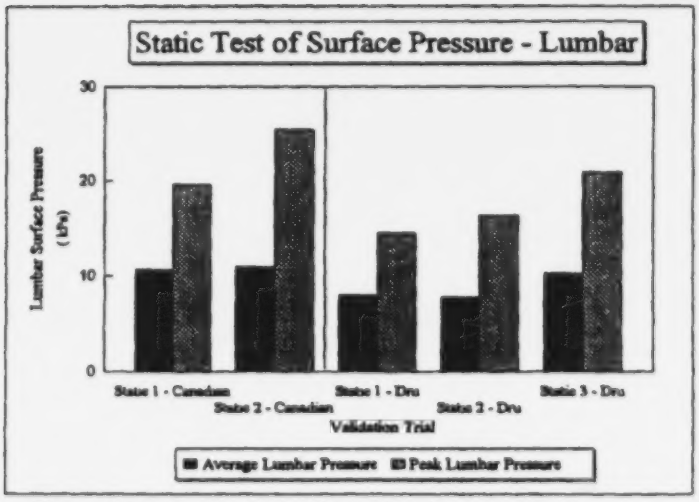
		Static		Dynamic	
		Pressure (kPa)	Area (m^2)	Pressure (kPa)	Area (m^2)
Shoulder	Average	6.3	0.003	15.2	0.005
	Peak	12.5	0.003	24.0	0.005
Waist	Average	8.2	0.004	2.1	0.005
	Peak	23.6	0.004	10.5	0.005
Lumbar	Average	8.7	0.006	8.6	0.011
	Peak	17.2	0.006	20.8	0.011



(a)



(b)



(c)

Figure D2 - 3 - Static testing of surface pressures
(a) Shoulder Surface Pressure (b) Waist Surface Pressure (c) Lumbar Surface Pressure

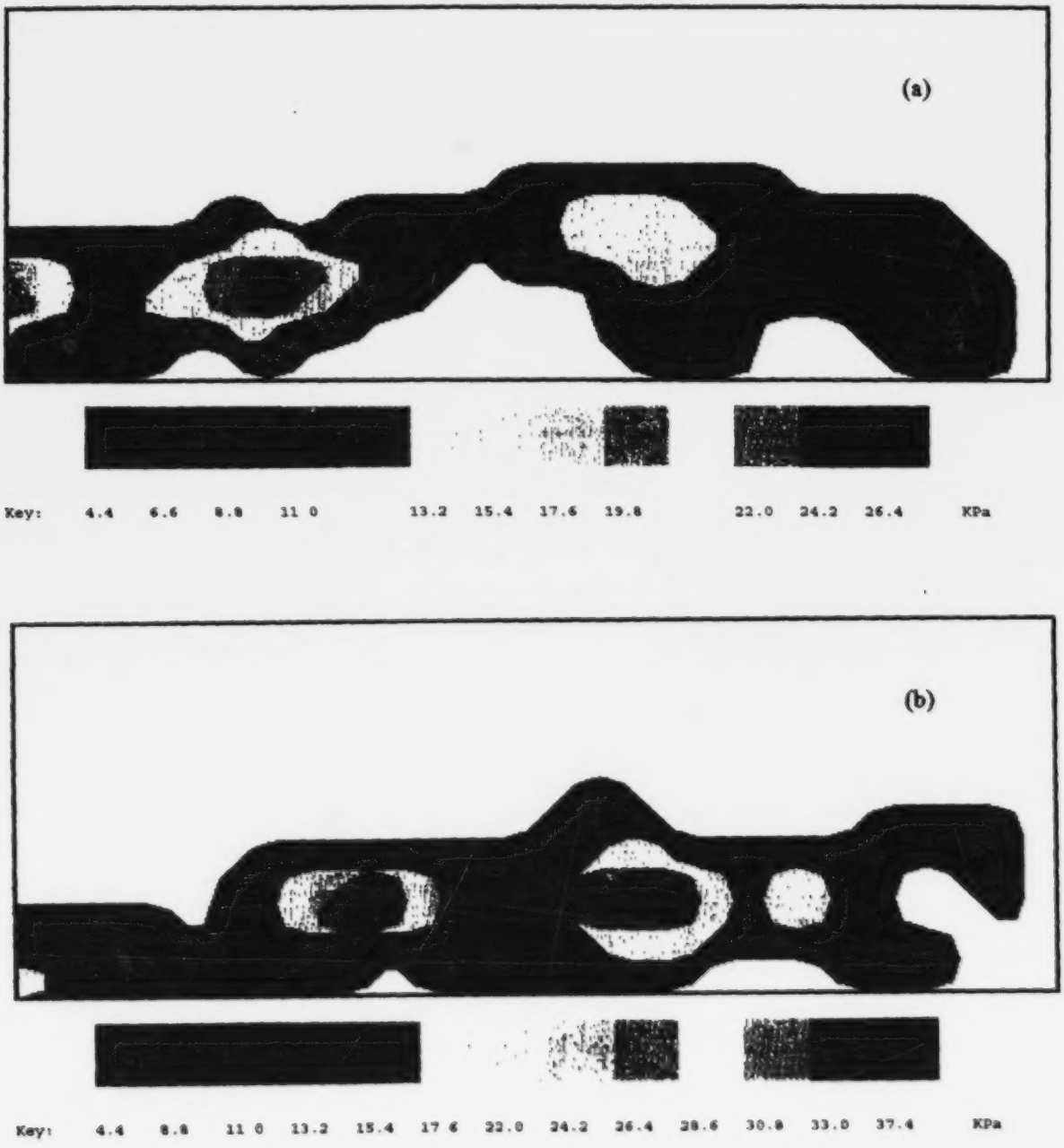


Figure D2 - 4 - Static shoulder surface pressures for Canadian 1982 pattern rucksack (a) Trial 1 (b) Trial 2

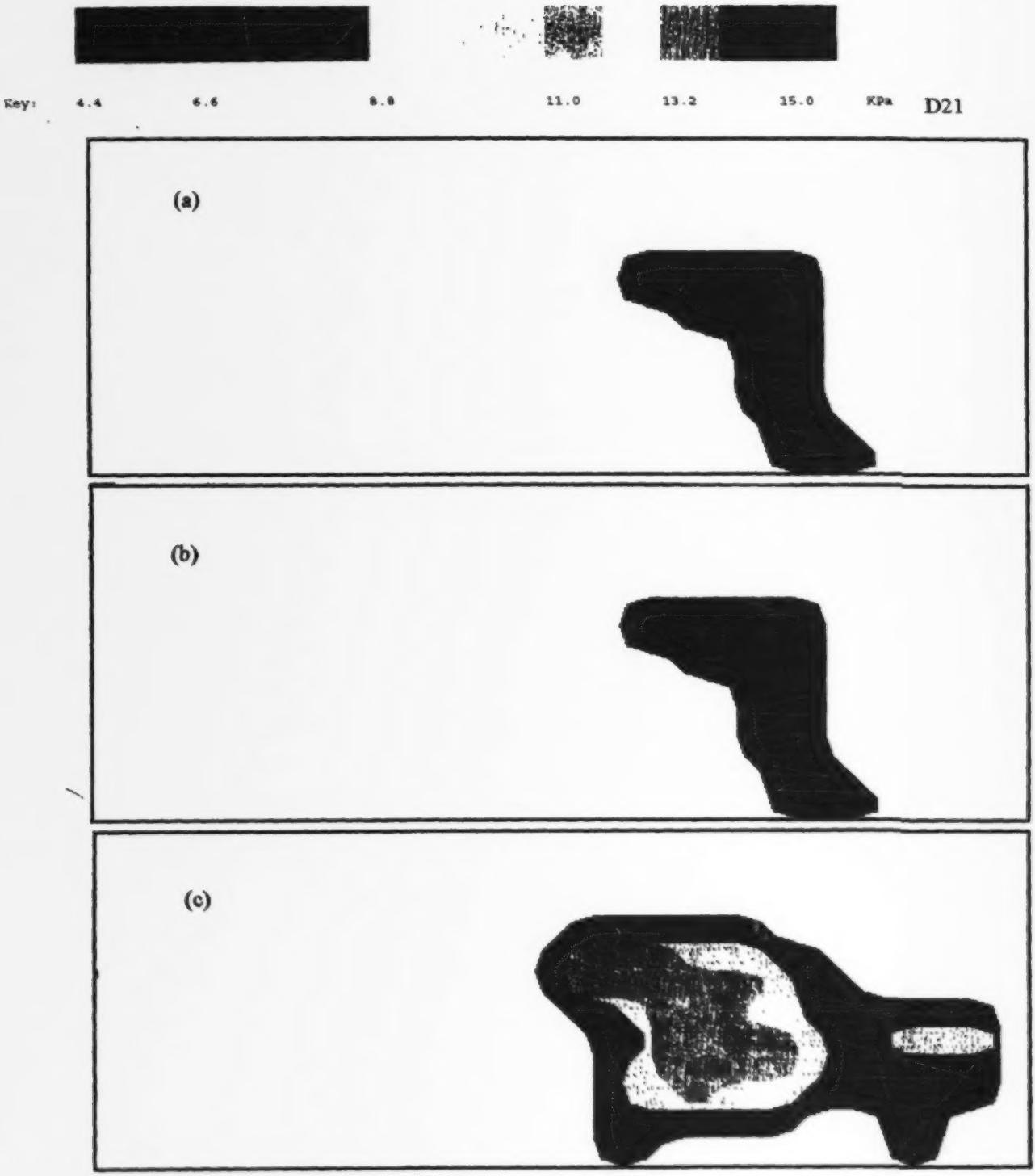


Figure D2 - 5 - Static shoulder surface pressures for Gregory Dru backpack
(a) Trial 1 (b) Trial 2 (c) Trial 3

D2.4 Pressure Sensing System - Dynamic Test

Introduction

Much of the discomfort and muscle fatigue experienced during load carriage may be directly attributable to the skin surface pressures generated by contact with the pack. Accurate evaluation of these pressures in a dynamic situation allows for an effective method of characterising the potential comfort of a load carriage system. Statistical analysis on the data gathered during four trials was performed to evaluate the accuracy and repeatability of the current pressure measurement system.

Methodology

A standardized test trial (see Appendix 9) was performed. Surface pressures were recorded at test times of 10, 300, 600, 900, and 1200 seconds, by means of skin surface pressure sensors. These sensors were calibrated and mounted under the locations of the shoulder strap, waist belt, and lumbar pad of the Canadian 1982 pattern rucksack prior to testing. Pack placement was verified by measuring the forces in the shoulder strap and waist belt, and adjusting to appropriate levels, as determined during field testing. Four trials were completed with the Canadian pack.

Results

A comparison of the average and peak skin surface contact pressures generated in the shoulder, waist, and lumbar areas for all trials can be found in Figures D2 - 6 (a), (b), and (c) respectively. Average skin surface pressures were calculated by dividing the sum of the forces experienced on the pressure sensor by the active area of loading. Both values were obtained from the TEKSCAN © software. Peak pressures were also supplied by the software. Table D2 - 7 also includes a summary of this data, with accompanying statistical analysis. Figures D2 - 7 (a), (b), (c), and (d) show the pressure plots recorded from the right shoulder sensor at test time equal to 1200 seconds in the four dynamic trials.

Discussion

The small standard deviations (1.0 kPa <SD<2.6 kPa) calculated for the average pressure values in the shoulder, waist, and lumbar areas, as shown in Table D2 - 7, indicate that these values

are consistent from trial to trial. This observation is confirmed by the small standard error of the mean values (< 1.3 kPa) calculated for average trials in all three pressure sensitive areas. A visual inspection of the average pressure values found in Figures D2 - 6 (a), (b), and (c) also shows that the data are repeatable across tests.

Peak pressure values showed more variation across tests. This result, as previously explained in Section D2.3, was a function of the nature of pressure peaks. Wrinkles in clothing or strap material, or clothing seams are typical peak pressure areas during load carriage. During dynamic testing, it was possible for these deformities to appear and disappear in the same test. This effect created temporary 'superpeaks' which provided high pressure values. Table D2 - 7 shows that peak values for all locations display a much larger standard deviation (3.7 kPa <SD<12.6 kPa) than do the average values. The standard error of the mean is also larger in the peak cases, particularly in the shoulder area (SE = 6.3 kPa). Figures D2 - 6 (a), (b), and (c) visually confirm that the peak pressure data are more widespread than the average values.

A calculation of the sample size necessary to provide a standard error of the mean less than 2.0 kPa with a confidence level of 95 per cent was also performed, with results found in Table D2 - 8. The table illustrates that low numbers of average pressure trials (1 - 2 trials) can provide a suitable degree of accuracy. The same is not true, however, for the peak case where the number of trials necessary to ensure an error of less than 2.0 kPa range from 4 to 40. Clearly, it is necessary to sacrifice the repeatability of peak pressure magnitudes to allow for a complete test to be run in a reasonable time frame. Further study may reduce the variability of the peak pressure values.

Plots of the pressure recordings made from the shoulder sensor at test time = 1200 seconds, as shown in Figures D2 - 7 (a), (b), (c), and (d), show a definite consistency in shape and location of peak pressure zones. All plots contain the same area of loading (A = 0.006 m^2) and series of three high pressure areas. These zones, identical to the results from the first load carriage test of the Canadian rucksack, are caused by surface details on the shoulder strap, specifically the load lifter strap buckle, the stitching between Velcro™ quick release tab and regular strap, and the stitching for the chest strap D - ring.

Table D2 - 7 - Dynamic test of surface pressures - Canadian 1982 pattern rucksack

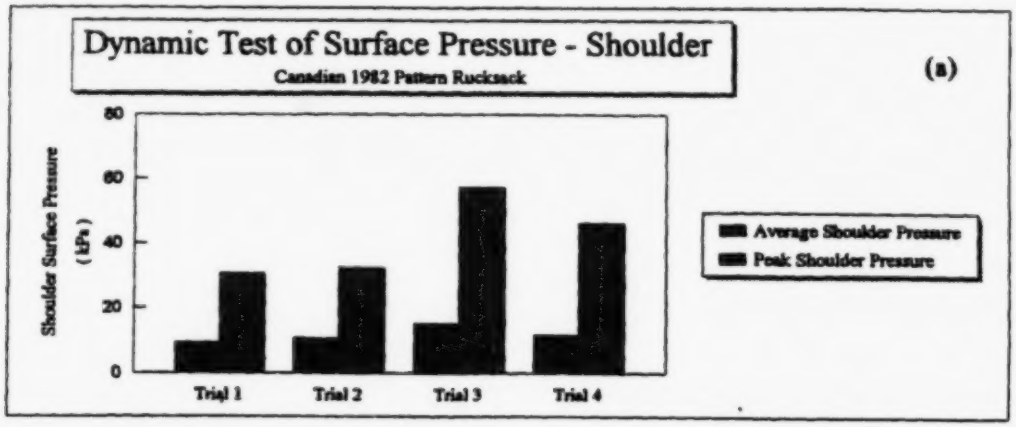
Dynamic Test Of Surface Pressures Canadian 1982 Pattern Rucksack						
Trial	Shoulder		Waist		Lumbar	
	Average (kPa)	Peak (kPa)	Average (kPa)	Peak (kPa)	Average (kPa)	Peak (kPa)
Dynamic 1	9.2	30.4	7.5	11	7.4	15.2
Dynamic 2	10.6	32.2	5.7	9.2	8.2	17.1
Dynamic 3	15.2	57.2	5.7	11.8	10.8	21.8
Dynamic 4	11.5	46.2	7.3	17.7	11.3	25.4
Mean (kPa)	11.6	41.5	6.6	12.4	9.4	19.9
Sample Variance (kPa^2)	6.6	159.4	1.0	13.5	3.7	21.3
Standard Deviation (kPa)	2.6	12.6	1.0	3.7	1.9	4.6
Standard Error (SE) (kPa)	1.3	6.3	0.5	1.8	1.0	2.3
Standard Error As % Of Mean	11.0	15.2	7.5	14.8	10.2	11.6
Sample Size Required For SE<2.0 kPa With 95 % Confidence	2	40	1	4	1	6

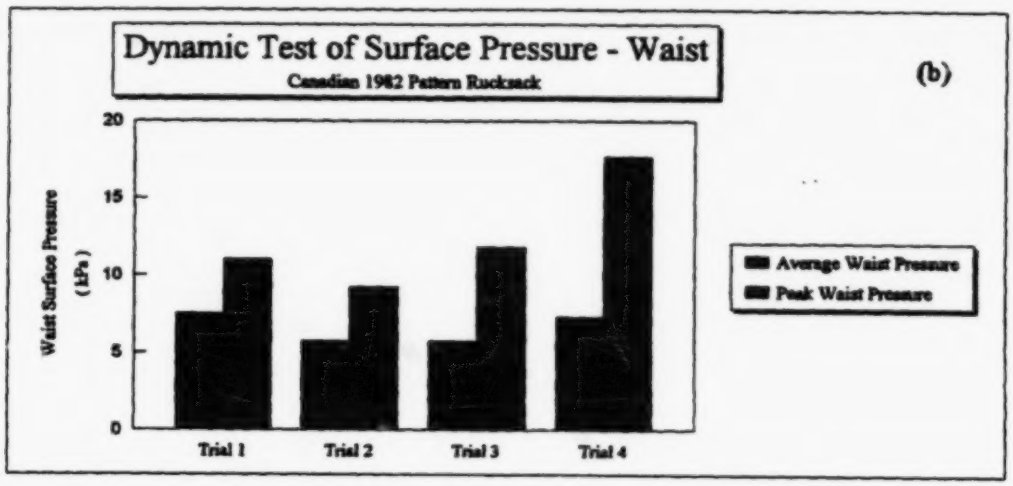
Conclusions and Recommendations

The need for accuracy in the collection of pressure data from load carriage makes it necessary to perform at least two trials per pack model, as explained in the previous subsection, to ensure quality data on average contact pressure generated. Similarly, larger standard errors of mean must be accepted in terms of peak pressure results to be calculated. For example, with a standard error of the mean = 4.0 kPa, it would be possible to ensure accuracy of peak results, with 95 % confidence, after collecting data from 10 trials. Further examples are included in Table D2 - 8.

Table D2 - 8 - Standard errors and associated sample sizes for dynamic pressure testing (with 95 % confidence)

Standard Error of Peak Pressures (kPa)	Sample Size for 95 % Confidence
2.0	40
2.2	33
2.5	26
3.0	18
4.0	10
5.0	6
6.0	4





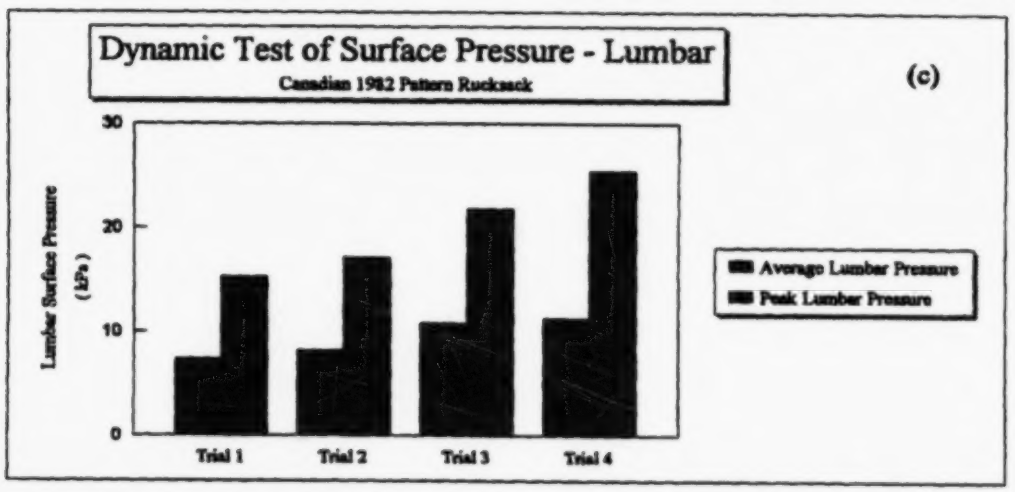


Figure D2 - 6 - Dynamic test of surface pressure - Canadian 1982 pattern rucksack
(a) Shoulder surface pressure (b) Waist surface pressure (c) Lumbar surface pressure

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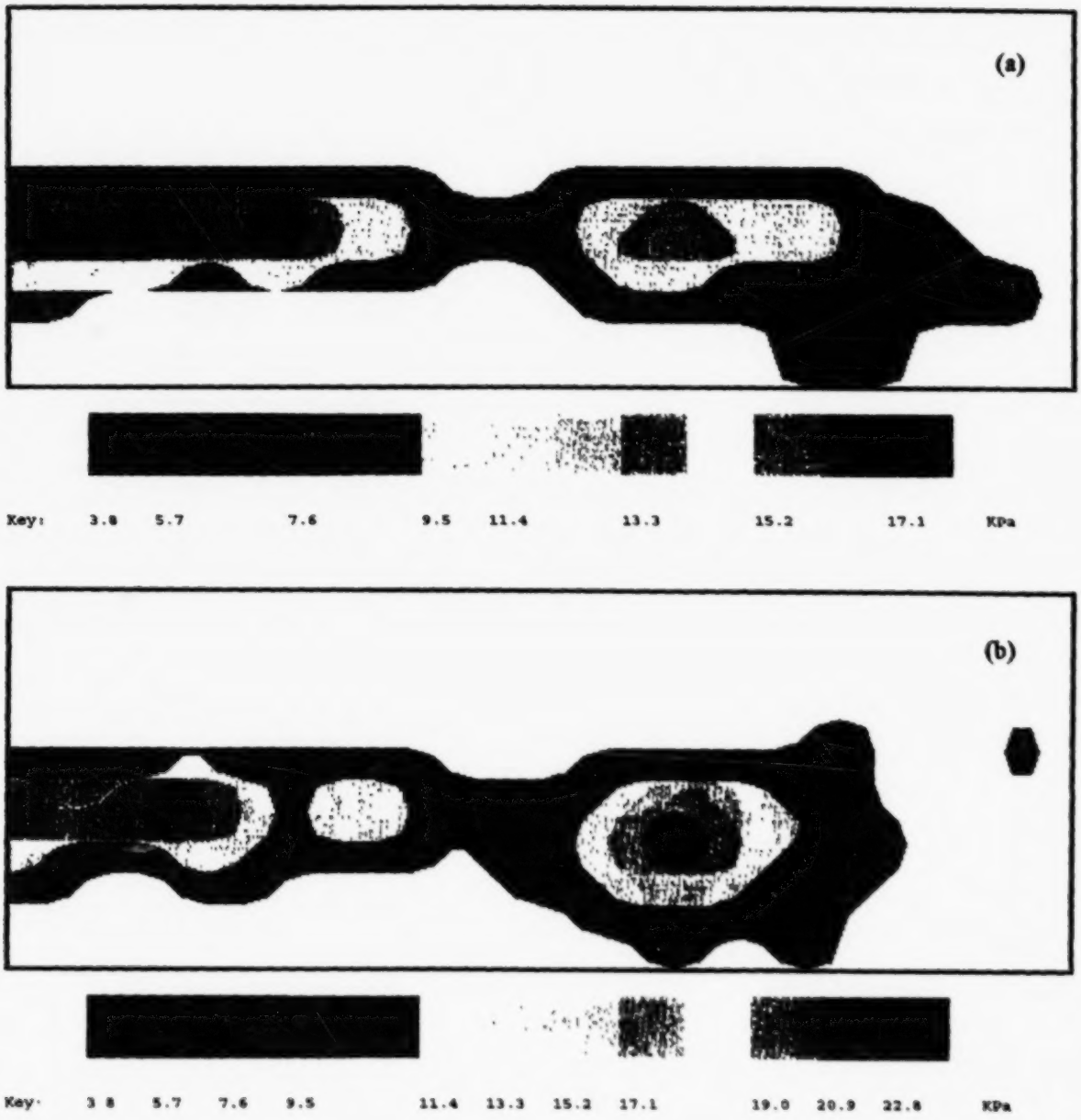
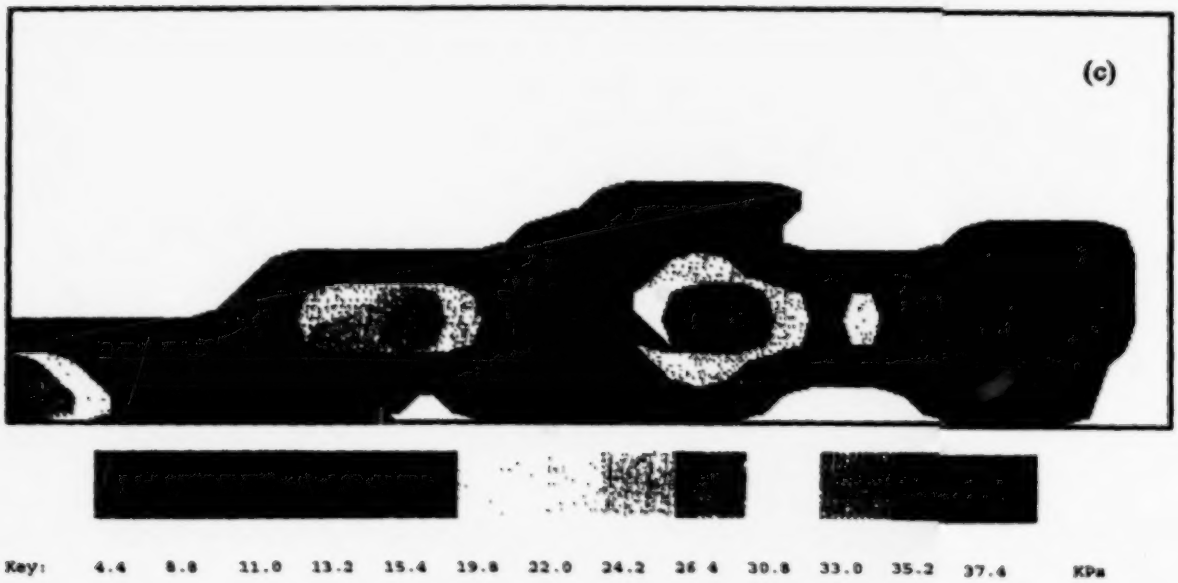


Figure D2 - 7 - Shoulder surface pressure plots - Canadian 1982 pattern rucksack
(a) Dynamic trial 1 (b) Dynamic trial 2



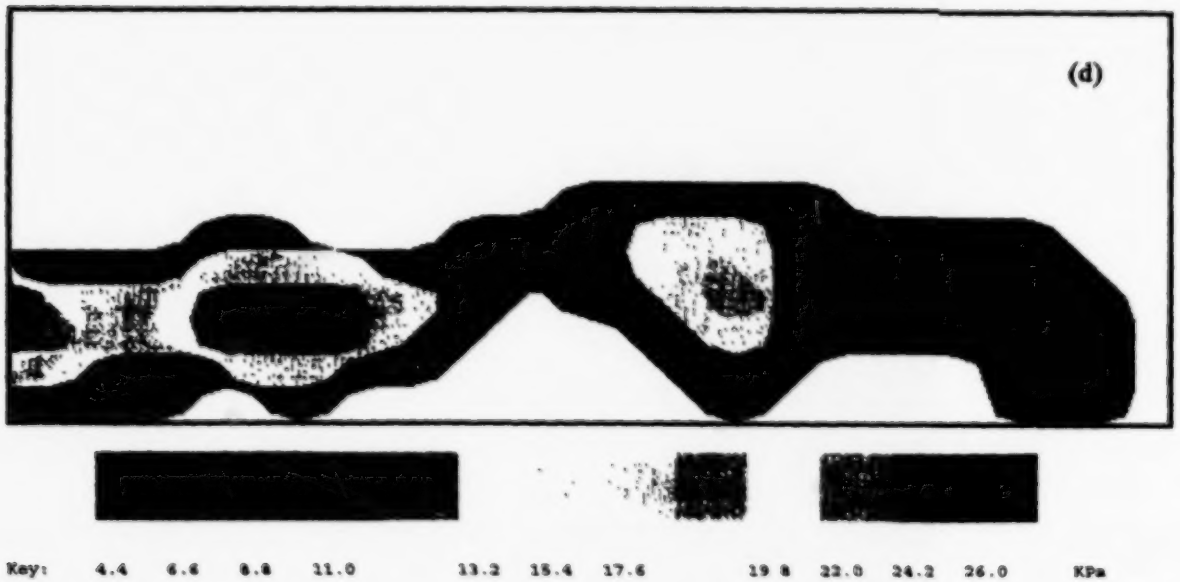


Figure D2- 7 - Shoulder surface pressure plots - Canadian 1982 pattern rucksack
(c) Dynamic trial 3 (d) Dynamic trial 4

D2.5 Relative Displacement of Pack - Static Test

Introduction

As the FASTRAK ™ sensors move closer and farther from the large concentration of steel and electronics at the Simulator's base, there may be an increase in the variability in the FASTRAK™ relative displacement results. This test was undertaken to determine the accuracy and repeatability of the FASTRAK ™ vertical displacement data in a static application. The OPTOTRAK ™ technology consists of three precisely positioned co-linear cameras which triangulate on sequentially pulsed LED's (active markers) to determine the three dimensional position of each LED. This image information is processed by the OPTOTRAK ™ software and X,Y,Z coordinates (lens-based coordinate system) are reported. Three active markers are required to calculate the position and rotation of each rigid body being monitored. This technology is impervious to variations in magnetic fields and when used in accordance with the manufactures instructions has an accuracy of +/0.1 mm. In a test retest sequence, the OPTOTRAK ™ was used to validate FASTRAK ™ data.

Methodology

Using the placement of the OPTOTRAK ™ LED's and the Load Carriage Simulator setup used in the dynamic testing shown in Figure D2-8, the base plate was moved vertically in a series of steps. Two ground steel supports were placed on the LC Simulator table and equal vertical steps were created by inserting melamine coated sheets of compressed fibreboard (nominal thickness 16 mm) between the steel supports and the base plate.

A test sequence was created by starting at the lowest position and sequentially moving up to highest position. This was repeated, moving from the highest position then, back to the lowest. Data were recorded using the FASTRAK ™ and the OPTOTRAK ™ at each of the six vertical positions. The FASTRAK ™ was programmed to record 14 samples, drop the two leading and trailing values, and report the average of the remaining 10 samples. Fifteen samples were averaged for each of the OPTOTRAK ™ data points used for comparison. No further calibration or manipulation of the FASTRAK ™ data was done. The test range covered 96mm of vertical displacement and a level walking test typically occurs between positions 2 and 4.

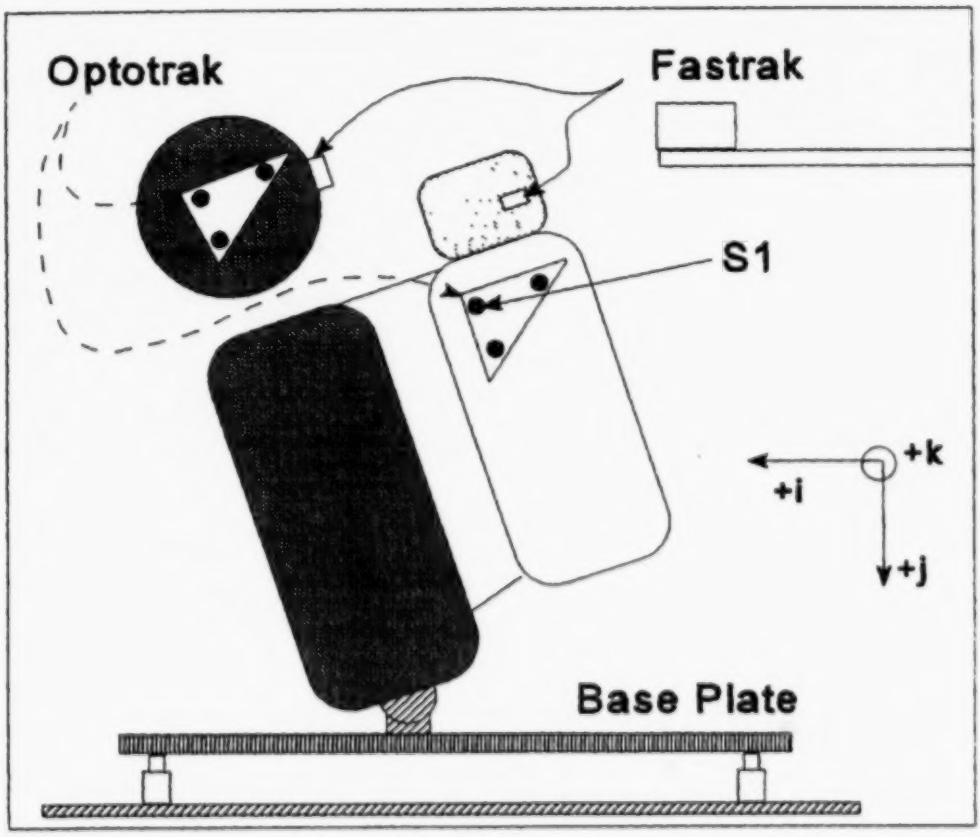
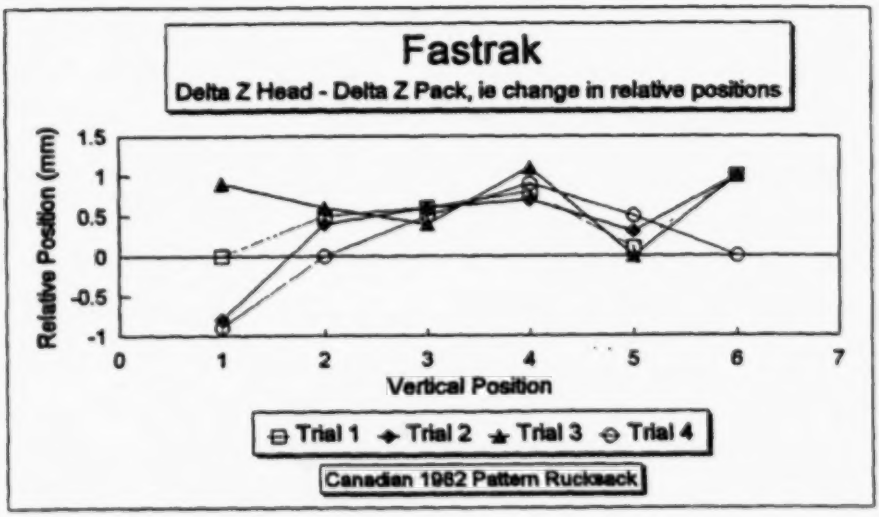


Figure D2-8. Displacement test setup. The FASTRAK ™ pack sensor is at P = (-60i, -80.6j, -154k) where P is the position vector from OPTOTRAK ™ Sensor S1 to the FASTRAK ™ sensor.

(a)



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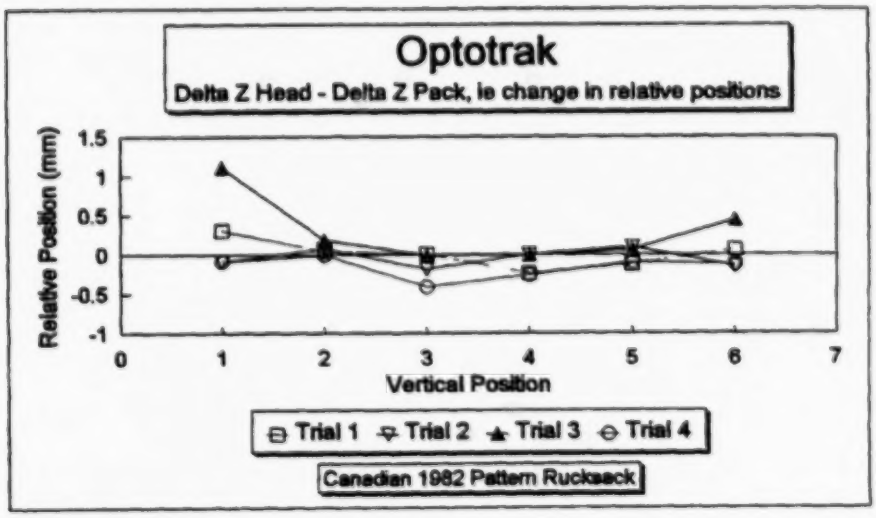


Figure D2-9. The measured change in the position of the rucksack with respect to the head.

Results

The change in the relative position of the payload with respect to the head (this is the parameter used to determine the laxity of a LC suspension system) was calculated for each vertical position using OPTOTRAK ™ and FASTRAK ™ data. These results are plotted in Figures D2-9 a) and b) and summarized in Table D2-9.

Table D2-9. RMS Error of FASTRAK ™ Position Data compared to OPTOTRAK ™

Description of Data	RMS value (mm) (all positions)	RMS value (mm) (position 2-5)
Head Position	0.46	0.24
Pack Position	0.44	0.26
Head-Pack (relative position)	0.65	0.66

Discussion

The RMS error of the FASTRAK ™ data is 0.65mm in a static test. There is no apparent decrease in ability of the FASTRAK ™ data to measure the relative displacement of the pack throughout the 96mm test range. There is a decreased accuracy in measuring the absolute position of the head or the pack at the extremes of the test range.

Conclusions and Recommendations

The following conclusions and recommendations were drawn from this study:

1. If absolute position data are required, only measures in excess of 0.65mm can be considered as a difference due to the laxity of the LC suspension system of a pack. It may be possible to improve this with extensive calibration of the FASTRAK ™ .

2. If absolute position data are required, the proximity of the FASTRAK ™ sensors to the LC Simulator support table in the lowest 30mm of stroke, will limit the accuracy of the data without further calibration effort.

D2.6 Relative Displacement of Pack - Dynamic Test

Introduction

This series of dynamic tests were undertaken to determine the accuracy and repeatability of the FASTRAK ™ displacement data. Two FASTRAK ™ sensors, one mounted on the mannikin and one on the pack were used to detect relative motion between the pack and the person.

The FASTRAK ™ technology (magnetic field sensing) is subject to a number of physical limitations. Due to the nature of electromagnetism, movement of metals, electrons and local magnetic fields within the magnetic field generated by the FASTRAK ™ source may effect the accuracy of the measured positions. Test structures and the internal components of different Load Carriage designs can potentially effect the FASTRAK ™ data.

The OPTOTRAK ™ technology consists of three precisely positioned co-linear cameras which triangulate on sequentially pulsed LED's (active markers) to determine the three dimensional position of each LED. This image information is processed by the OPTOTRAK ™ software and X,Y,Z coordinates (lens based coordinate system) are reported. Three active markers are required to calculate the position and rotation of each rigid body being monitored. This technology is impervious to variations in magnetic fields and when used in accordance with the manufacturers instructions, has an accuracy of ±0.1 mm. In a test/retest sequence, the OPTOTRAK ™ was used to validate FASTRAK ™ data.

Methodology

The Load Carriage Simulator was set up with the Canadian 1982 Pattern Rucksack according to the standard test protocol (Appendix 9). A plate was rigidly attached to the side of the mannikin's head and directly on the pack payload. Three OPTOTRAK ™ LED's were mounted in a triangle (approximately 80mm each side) on each plate. Two additional LED's were mounted onto the top edge of the LC Simulator support table and a final two were attached to the side of the base plate (see Figure D2-8).

Two complete 1200 cycle (20 minute) level walking tests were then conducted. The pack was removed and repositioned between tests. Position data were recorded at 55 Hz for 18 seconds every 300 cycles. Using the OPTOTRAK ™ and FASTRAK ™ data, the relative displacement of the payload with respect to the head of the body, was calculated. No calibration or manipulation of the

FASTRAK ™ data was applied. The OPTOTRAK ™ data were then mathematically translated to be coincident with the location of the FASTRAK ™ sensor. These data were then filtered using a two pass Butterworth filter using a cutoff frequency of 25 hz.

Results

The position "F" of the FASTRAK ™ sensor in the pack was measured with respect to the OPTOTRAK ™ LED's using a pack-based coordinate system, vector P. The rotation of this pack-based coordinate system was then determined by calculating the rotation in space of the OPTOTRAK ™ LED's mounting plate throughout the test period. This rotation was applied to the P position vector to determine the position of "F" in global coordinates. Since rotation about the vertical axis is fixed in the LC Simulator, this was assumed to be zero for the pack.

The relative displacement of the pack with respect to the head is the parameter used to evaluate the laxity of a LC suspension system. This parameter was calculated directly from the FASTRAK ™ data. FASTRAK ™ data are plotted with the raw OPTOTRAK ™ data in Figure D2-10, with the transformed coincident OPTOTRAK ™ data in Figure D2-11 and with filtered coincident OPTOTRAK ™ data in Figure D2-12.

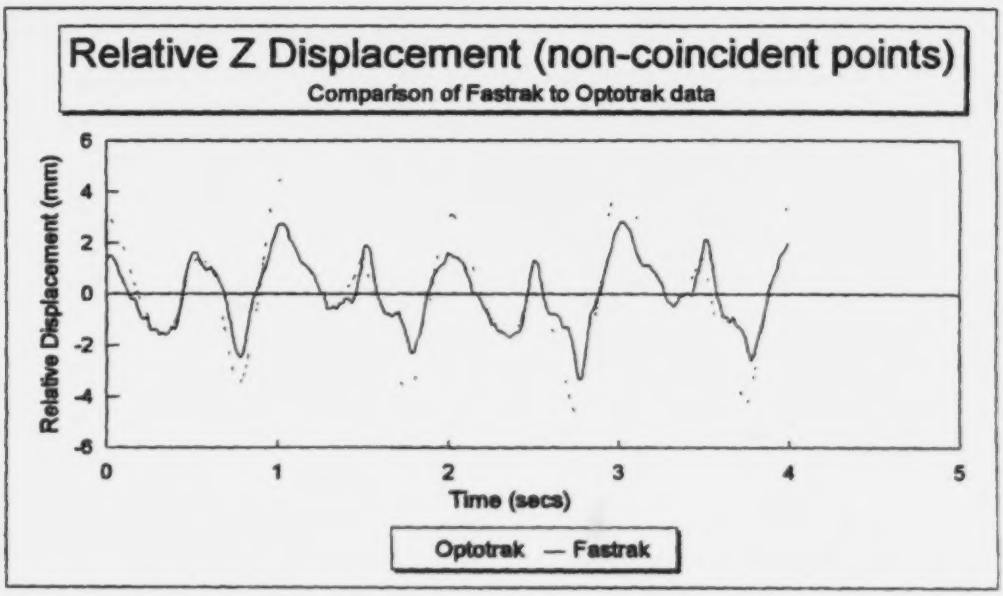
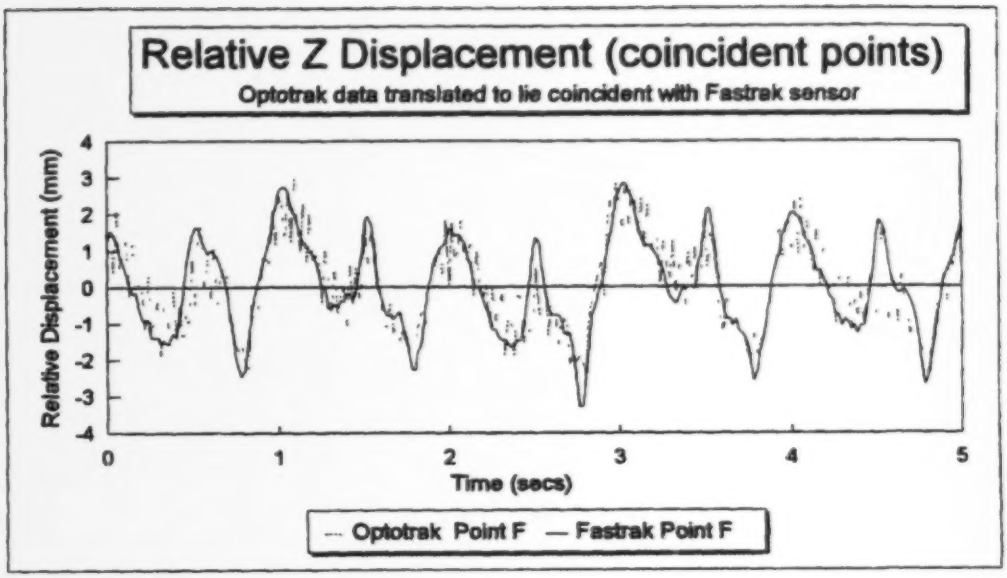


Figure D2-10. Vertical movement of the pack relative to the head, FASTRAK ™ data compared to raw OPTOTRAK ™ data.



Total Displacement (mm) **RMS Error of FASTRAK ™ data**: 0.65 mm

	FASTRAK ™	OPTOTRAK™
Max.	2.99	2.82
Min.	-2.35	-3.28
Peak to Peak	5.34	6.10

Figure D2-11. Vertical movement of the pack relative to the head, FASTRAK ™ data compared to transformedOPTOTRAK ™ data. The OPTOTRAK ™ data has been translated to lie coincident with the FASTRAK ™ sensor.

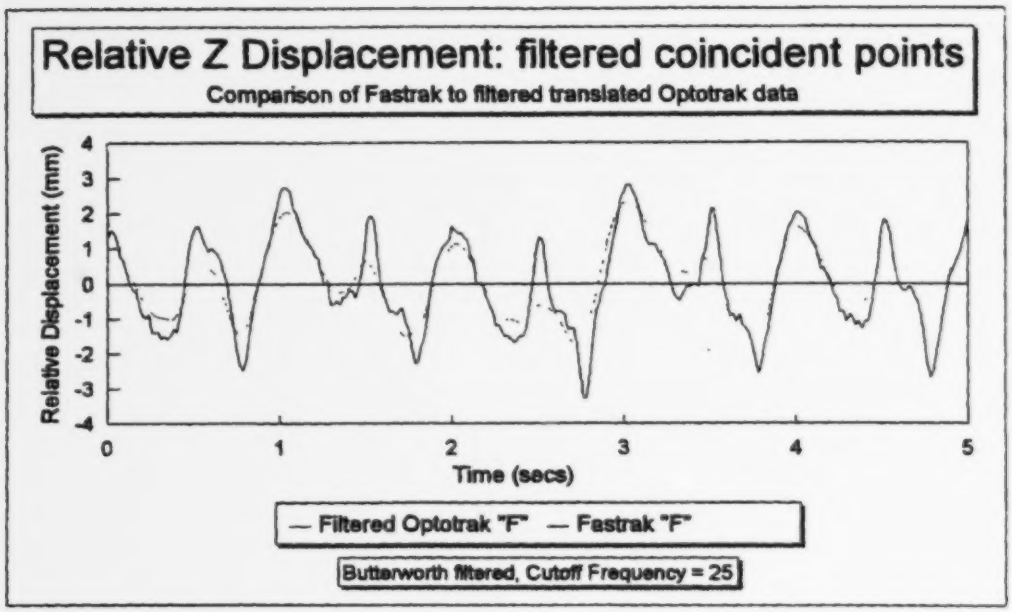


Figure D2-12. Vertical movement of the pack relative to the head, FASTRAK ™ compared to filter OPTOTRAK ™ data. The OPTOTRAK ™ data has been translated to lie coincident wi the FASTRAK ™ sensor and filtered with a two pass Butterworth filter, (cut off frequen = 25).

Discussion

The apparent noise in the OPTOTRAK ™ transformed data (Figure D2-11) was due to t method of calculating the rotation angles. The expression "arctan((y2-y1)/(x2-x1))" was used to determi the incremental rotation of the pack making the transformation ill-conditioned when the value of (x2-x approaches zero. The FASTRAK ™ is reporting the relative displacement of the pack to within 0.65 m This level of accuracy is adequate to classify the performance of LC suspension systems and to establi a rank order of results as reported in Section B of the main report.

Conclusions and Recommendations

The following conclusions are drawn from this study:

1. In dynamic testing, only changes in the relative displacement between the pack and the person that are greater than 0.65 mm can be attributed to the pack and its' suspension system.

2. Since a pack does rotate slightly with respect to the global reference frame, in order to directly compare pack displacements, the FASTRAK ™ sensor should be positioned at the centre of gravity of the pack.

Section D3

Load Carriage Biomechanical Model

D3.1 Review of Current Model

D3.2 Method to Validate Shoulder Model

D3.3 Results and Discussion

D3.4 Conclusion and Recommendations

A biomechanical model was developed in Phase I as a method for approximating the force distribution between the backpack and the torso. The purpose of this section is to validate the shoulder model by developing a theoretical framework for the shoulder reaction forces and then compare two methods of input to the model: the strap forces and the strap pressures.

D3.1 Review of the Current Model

The APLCS mathematical model from Section B2.5 of this report was simplified to reduce the number of unknowns to create a statically determinate approximation of the force distribution between the pack and the torso. The free body diagram of the pack is repeated in this section as Figure D3.1. The lower and upper strap forces are represented by T1 and T2 respectively.

The force distribution on the torso is highly influenced by the design of the upper strap (T2) such that small changes in the upper strap angle greatly influenced the predicted tension in the upper strap transmitted to the torso. Both the angle at which T2 meets the pack and the force on T2 are difficult to measure because of pack geometries. Therefore T2 was calculated in the existing mathematical model, based on resolving T2 into horizontal and vertical components (Figure D3.1). Using the measured T1 and a number of pack orientations and dimensions, the third calculated output of the model was the lumbar pad force (Fh). The waist strap forces were not considered in the existing biomechanical model. The inclusion of the horizontal waist belt tension would have created a fourth unknown and therefore rendered the model statically indeterminate. The exclusion of the waist belt forces from the model leaves the model incomplete.

D3.2 Method to Validate the Shoulder Model

This investigation was designed to determine the coefficient of friction between the mannikin's shoulder and the shoulder strap in a typical pack configuration. The torso was fitted with a combat shirt and pressure sensors and the shoulder strap from the Dru was then removed from the pack.

A testing apparatus, shown conceptually in Figure D3.2, was constructed to simplify the testing protocol. A mannikin, filled with rigid polyurethane foam and supported on a steel post was constructed and covered with Bocklite, a synthetic skin to simulate normal tissue compliance. The shoulder straps were attached via strap force transducers to a solid wall. The shoulder strap adjustment was intact and therefore could be tightened at the bottom of the strap. The lower strap force was manipulated in a range of appropriate tensions (40 N to 75 N). The pressure experienced by the shoulder and the changes in the upper strap forces (T2) were monitored and recorded. This experiment was performed ten times at three different wrap angles: 115, 122 and 131 degrees.

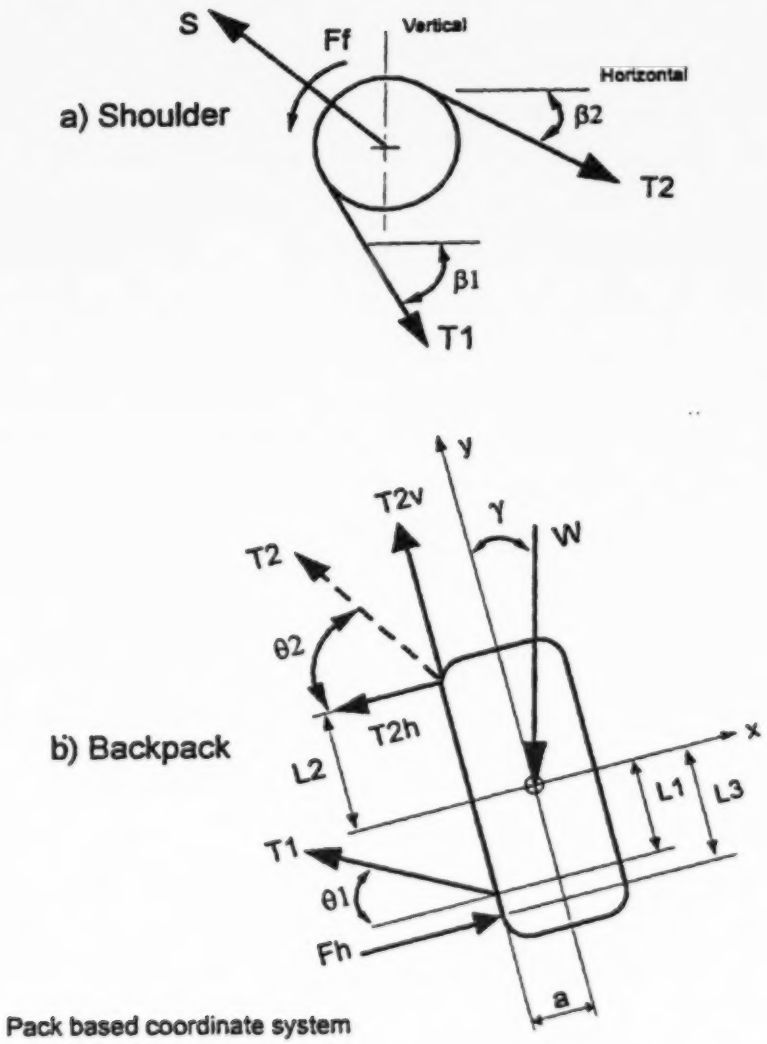


Figure D3 - 1 - Biomechanical models of the shoulder, pack and torso.

(a) Free body diagram of the shoulder (b) Free body diagram of the pack

The wrap angles were altered between trials by changing the location of the bottom strap attachment point.

It was possible to verify the classical model of a pulley with friction by measuring T1 and T2 and the measured reaction force under the strap. The latter could be determined from the integration of the pressure distribution determined by the Tekscan© system described in Section D2. The measured normal force (Fn) from under the sensor is not the same as the shoulder reaction force (S) and does not appear on the free body diagram of Figure D3.1.

From Equilibrium along the strap,

$$Ff = T2 - T1 \qquad \textit{Equation 1}$$

From the classical pulley equation (Beer & Johnston, 1976, p. 310)

$$T2/T1 = e^{\mu\theta} \qquad \textit{Equation 2}$$

Since Fn is also measured, two approximations for the coefficient of friction, μ, are possible.

By definition, $\mu = Ff/Fn$, thus from Equation 1:

$$\mu = \ln(T2/T1)/\theta \qquad \textit{Equation 3}$$

Also, from the pulley equation (Equation 2):

$$\mu = (T2 - T1)/Fn \qquad \textit{Equation 4}$$

The coefficient of friction was calculated for each of the 30 trials for each angle of wrap. The mean coefficient of friction for each wrap angle was calculated.

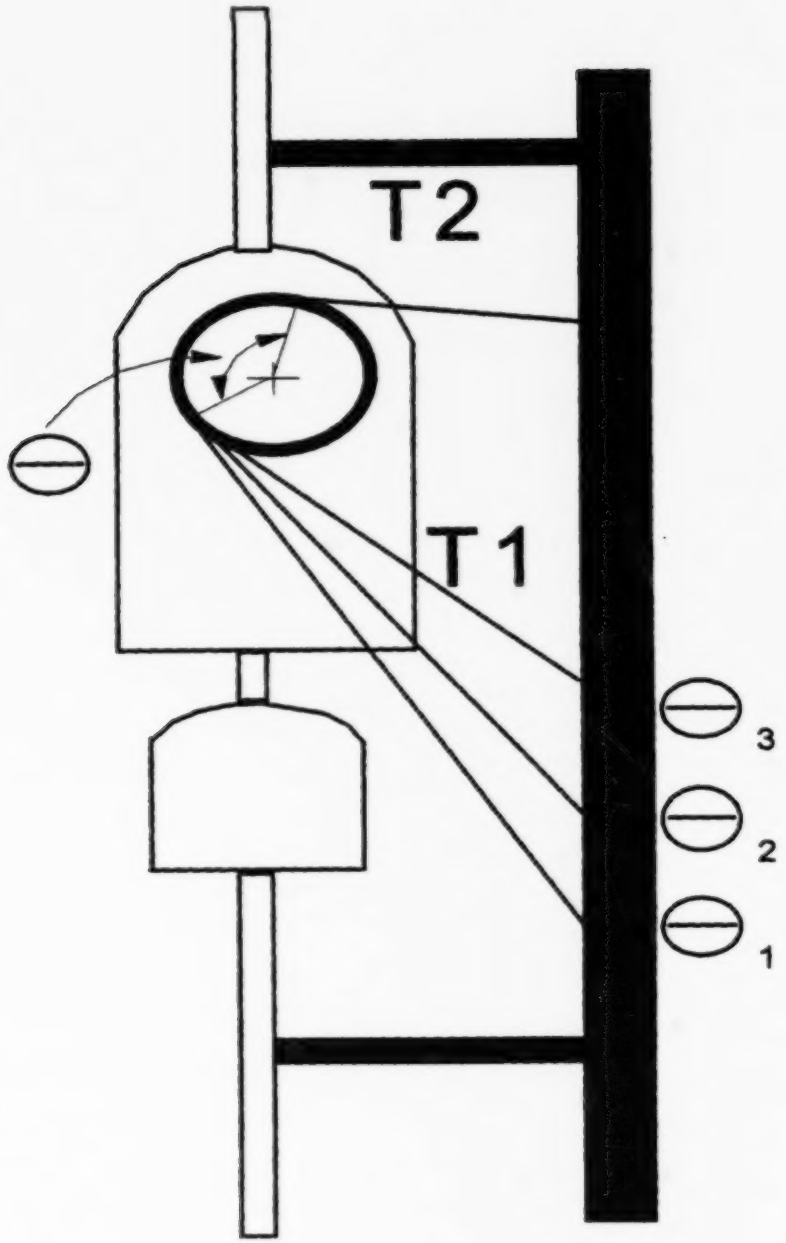


Figure D3 - 2 - Schematic of the Shoulder Model Validation Apparatus. Strap transducers measure strap tension (T1 & T2).

D3.3 Results & Discussion

After measuring T1, T2 and the pressure across the shoulder, the coefficient of friction between the shoulder and the Dru shoulder strap was calculated using the two methods. Both calculations used T1 and T2 but the first calculation of the coefficient of friction used the two force measurements and the wrap angle and the second method used the pressure measurement. The results are depicted in Table D3.1. The calculated coefficient of friction using the angle of wrap consistently produced a higher average coefficient of friction.

Table D3 - 1 - Coefficient of Friction between the Shoulder and the Dru Pack Strap

Method	115 Degrees (n=30)		121 Degrees (n=30)		131 Degrees (N=30)		Average (n=90)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
$\mu = \ln(T2/T1)/\theta$	0.075	0.03	0.064	0.04	0.065	0.04	0.068	0.037
$\mu = (T2 - T1)/Fn$	0.061	0.03	0.058	0.04	0.064	0.04	0.061	0.037
							0.065	0.037

A paired t-test produced a non-significant difference between the two coefficient of friction methods ($\alpha = 0.05$). Therefore, it is acceptable to use either method as an approximation of the coefficient friction in order to calculate T2.

A method to allow the estimation of T2 from T1 and the pressure data would facilitate the inclusion of the waist belt forces into the model. Therefore, T2 was estimated using T1, the pressure data and the average coefficient of friction ($\mu = 0.065$) from the previously collected data using Equation 4. The calculated T2 was then compared to the measured T2. The results are included in Table D3.2. A paired t-test produced a non-significant result ($\alpha = 0.05$), indicating that the calculated T2 and the measured T2 are not significantly different. Although this is to be expected from these data (since μ was calculated from the same values), the analysis serves to indicate the expected error in T2 when T1 and μ are used in its estimation.

Table D3 - 2 - Measure T2 Values vs Calculated T2 Values

Wrap Angles	Measured T2	Calculated T2	Std Error of Estimate
115 ° (n=30)	56 N	47 N	3.7 N
121° (n=30)	55 N	56 N	5.4 N
131° (n=30)	54 N	54 N	5.7 N

D3.4 Conclusions and Recommendations

Two independent strategies were used to determine the magnitude of the coefficient of friction (μ) and the results revealed no significant difference between the two methods using the average μ value, the lower strap (T1) force and the pressure readings. The upper strap (T2) force was calculated. The standard estimate of the error indicates that T2 can be estimated within 10 %. The T2 values calculated using the coefficient of friction are lower than the predicted T2 values from the original biomechanical model. The impact of the lower T2 estimation will reduce the suggested load distributions on the shoulders. The original model suggested load distributions ranging from 70-80% on the shoulders. These numbers are likely to drop when the new T2 model and the waist belt factor is included in the new model.

Appendix 9 :

LC Simulator

Test Protocols

Appendix 9: LC Simulator Test Protocols

1.0 Introduction

Repeatable testing procedures provide a solid basis for quality data collection, and therefore strong scientific conclusions in experimental testing. This section details the steps followed for a full LC simulator test of one backpack style. Subsections describe testing procedures used to gather specific quantitative data sets.

2.0 Basic Test Protocol

2.1 Equipment

a) Load Carriage Model:

i) each load carriage model was packed to a mass of 25 kg of steel plate (+/- 1 kg)
ii) steel plates were held in place by a Styrofoam pack insert, which filled the pack shape and maintained the payload position
iii) a reaction board was used to measure the centre of gravity of each pack, which was referenced against field measurements of the centre of gravity of packs carried by expert trekkers
iv) strap force transducer retaining loops were sewn onto the lower right shoulder strap and the waist belt of the pack. Loops were 8.0 cm apart and consisted of 2.5 cm wide nylon webbing material
v) a split ring with a hooked end was inserted in the upper loop of each set

b) Human Torso Model:

i) the torso was instrumented with three calibrated TEKSCAN © pressure sensors
ii) sensors were positioned on the skin surface in the area of contact with the right shoulder strap, the right half of the waist belt, and the centre of the lumbar pad for each pack
iii) torso was covered with a Canadian military combat shirt

c) Load Carriage Simulator:

i) simulator control was carried out by the 'APLCS.SEQ' command file (programmed by D. Siu, Clinical Mechanics Group, Queen's University) on the Keithley Metrabyte VIEWDAC © programmable control system
ii) operating air pressure for experimentation was 40 psi (275.6 kPa), which was regulated from line pressure
iii)when line pressure dropped below 50 psi (344.5 kPa) testing was paused. Testing resumed when line pressure exceeded 105 psi (723.5 kPa)
iv)simulator rest position was established by inserting 20.0 cm blocks underneath the plate. Testing began and ended at this rest position.

2.2 Method

a) Pack Placement:

i) load carriage system was placed in a normal carrying position on the model torso
ii) approximate positioning was confirmed with comparison to photos taken of soldiers in the field wearing the same load carriage model

b) Trunk Lean:

i) with load carriage on the torso model, the trunk lean bracket was released from the simulator plate
ii) forward lean was adjusted until the torso, with LC system, was balanced evenly on a 10 cm X 10 cm base
iii) trunk lean bracket was tightened and the lean angle was recorded

c) Strap Force Tensions:

i) strain gauges were held in a non-loaded position and their offsets were recorded with the VIEWDAC © program 'JAN96STR.SEQ' (S. Reid)
ii) straps were tightened until the voltage output from the strain gauges was within 10 % of the field testing results

3.0 Specific Test Protocol

3.1 Displacement Measurement

Equipment

A Polhemus Inc. FASTRAK © tracking system with one magnetic source and two sensors was used for displacement measurements.

Method

a) Calibration

i) the FASTRAK © source was fixed to the support post, clamped to the left side of the simulator table one sensor was permanently fixed to the centre back of the model head
ii) the second sensor was placed in 64 different positions (4 rows by 4 columns by 4 layers) in a calibration cube affixed to the top of the Styrofoam load carriage insert
iii) using the program 'SINGLE2.EXE' (programmed by B. Pearce, School of Physical Education, Queen's University) X, Y, and Z coordinate data were collected for each calibration position, with the torso leaned forward and the pack in place
iv) this data were translated to a global X,Y,Z system by using the 'FTCANCAL.WK4' spreadsheet (created by S. Reid, Ergonomics Research Group, Queen's University)
v) calibration between the translated FASTRAK © data and the absolute location of the calibration cube positions was performed with the 'TRACKCAL.EXE' program (B. Pearce)
vi) calibration equations were created for all data in the X, Y, and Z directions

Note: Given the results of the validation testing reported in Sections D2.5 and D2.6, this calibration procedure will not be repeated in future testing

b) Data Collection

i) after all steps in Section D3.2.2 were followed, the strain gauge transducers were removed

ii) the pack sensor was placed in the calibration cube position 2,2,2 (cell at second row, second column, second layer) and the entire cube was fixed to the pack insert
iii)test motion was initiated with the 'APLCS.SEQ' program
iv)FASTRAK © data was collected with the program 'BPACCEL2.EXE' (B. Pearce) when the test had reached 10, 300, 600, 900, and 1200 cycles
v) filenames were recorded as 'PACMMDDT.DIS' where:

PAC = pack identification (AME, BRI, CAN, DRU, EXT)
MM = month identification
DD = date of testing
T = time of collection (1 = 10 cycles, 2 = 300 cycles, etc.)

vi) any pause in the test cycle due to low air pressure was also a pause in the FASTRAK © cycle

3.2 Pressure Measurement

Equipment

Pressure measurements were collected with a FSCAN © system from TEKSCAN Technologies. This system included an A/D board, two pressure cuffs with cables, and a supply of pressure sensors (pressure sensitive ink generating resistance change)

Method

a) Calibration

i) prior to their placement on the torso model, sensors were loaded with a known amount of mass and calibrated using the manufacturer's software
ii) all sensors were evenly loaded during calibration and were supported on a thin layer (2 mm) of incompressible latex
iii)calibration files were saved under the filename 'S##.CAL' where:

S = sensor (does not change)
= sensor number (running tally of the sensors used)

iv) calibrated sensors were fixed to the model in the appropriate locations (see Section D3.2.1 (b)) in a non-permanent manner with spray adhesive (3M™ 77 spray)

v) sensors were checked for activity in a non-load state to ensure no wrinkling had occurred during placement

b) Data Collection

i) after all steps in section D3.2.2 were followed, the strain gauge transducers were removed
ii) readings from all pressure sensors were checked for activity
iii) appropriate calibration files were recalled
iv) static data recordings from all three sites were made with the manufacturer's program
v) test motion was initiated with the 'APLCS.SEQ' program
vi) shoulder and waist pressure data was collected with the TEKSCAN © program when the test had reached 10, 300, 600, 900, and 1200 cycles
vii) lumbar pressures were recorded at mid trial times (150, 450, 750, 1050, and 1350 cycles)
viii) filenames were recorded as 'PACKTttL.FSX' where :

PACK = pack identification (AME, BRI, CAN, DRU, EXT)
T = trial
tt = test time (00, 01, 05, 10, 15, 20 minutes)
L = location (1 = shoulder, 2 = waist, 3 = lumbar)

Note : lumbar recordings received tt stamp of previous shoulder and waist recording (e.g. Lumbar recording from 450 cycles has tt = 05)

ix) any pause in the test cycle due to low air pressure was also a pause in the pressure data cycle

3.3 Strap Force Measurement

Equipment

i) strap force transducers were comprised of four strain gauges (Micro Measurements Inc.) in a typical Wheatstone bridge arrangement on a carrier material of 6061 - T6 Aluminum Alloy.
ii) voltage output results were recorded with the VIEWDAC © program 'STRREC.SEQ'
iii) signal conditioning was performed on a 16 channel multiplexer board

Method

a) Calibration

i) strain gauges were supported at one end
ii) a known mass was supported by the opposite end and a reading of voltage output was made
iii)further readings were made as the mass was increased, generating a calibration curve for each transducer system

b) Data Collection

i) all steps in Section D3.2.2 were followed
ii) test motion was initiated with the 'APLCS.SEQ' program
iii) shoulder strap and waist belt strap force data was automatically collected with the 'STRREC.SEQ' program when the test had reached 10, 300, 600, 900, and 1200 cycles
iv) filenames were recorded as 'PACKT.DAT' where:

PACK = pack identification (AME, BRI, CAN, DRU, EXT)
T = trial

v) any pause in the test cycle due to low air pressure was also a pause in the strap force data cycle

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14. ABSTRACT

(U) A comprehensive measurement system for load carriage evaluation was developed and described in Section B of this report. This measurement system consisted of human input with respect to comfort, features and fit, as well as a standardized measurement system using a computer-controlled Load Carriage (CL) Simulator. The LC Simulator had been programmed to a walking cadence of 3 km/hr using computer controlled pneumatic actuators. Three pack assessment strategies were used to examine the effect of pack dynamics with respect to a standardized mannikin: a) strap force sensors on the shoulder straps and waist belt; b) pressure sensors under the shoulder and waist straps and lumbar pad; and, c) differences in motion between the pack and the person.

The purpose of this portion of the study was to validate the measurement systems used in the LC Simulator under both static and dynamic conditions, and to conduct a sensitivity analysis of the biomechanical model used to evaluate shoulder and lumbar forces.

In order to accomplish the first objective, independent measurement strategies were formed for each of the LC Simulator output measures. The second objective of validating the biomechanical model was initiated by developing a standardized jig for shoulder strap testing where strap forces, pressures, shoulder geometry and pack conditions could be evaluated independently. Custom-built shoulder strap and waist belt force transducers were used in static and dynamic conditions to assess standardized weights. The calibration algorithms were gauge dependent and highly linear (R^>.9995), with a small error (2.7 N) and were very stable over time in static testing. Under dynamic conditions the maximum standard deviation within tests was 0.9 N and across tests was 2.3 N with less that 4% decay over 1200 cycles.

The TELSCAN Pressure Sensor System under static conditions was more stable in average pressure and area of coverage than peak pressures, with the absolute value of peak pressures being more responsive to wrinkles in shirts or buckles. During dynamic conditions, over 1200 seconds of simulated walking trials the SEM for average pressures was .5 kPa to 1.3 kPa depending on the location and pack characteristics. Peak values were less stable (SEM of 3.7 kPa to 12.6 kPa), dropped in magnitude over time, and were better suited to identifying pressure points.

The FASTRAK assessment of relative displacement between the pack and the person was validated with the OPTOREACK system under both static and dynamic conditions. Results from the OPTOTRACK were transposed to correspond to a common coordinate system and a coincident measurement point. Regardless of test conditions, the pack/person relative positions had a .65 mm RMS error.

In the earlier biomechanical model reported in Section B, the upper shoulder strap was estimated from the lower shoulder strap tension, the shoulder wrap angle and approximations of the frictional forces. The first step of the validation involved determining by two independent strategies. One calculation technique involved using the values for the upper and lower strap forces and the angle of wrap while the second incorporated the pressure generated under the strap with the two strap forces. There was no significant difference in the results from the two different methods (R^.92). Hence, either method can be used to determine the upper shoulder strap forces. Further research is ongoing to validate the shoulder reaction force, load lifter straps, and to incorporate the waist belt.

15. KEYWORDS, DESCRIPTORS or IDENTIFIERS

(U)